Geological Survey of Canada
Commission géologique du Canada

PAPER 87-10

THE DESIGN, CONSTRUCTION AND APPLICATION OF AIRBORNE GAMMA-RAY SPECTROMETER CALIBRATION PADS — THAILAND

R.L. GRASTY

Canada

1987

87-06389/

GEOLOGICAL SURVEY OF CANADA
PAPER 87-10

THE DESIGN, CONSTRUCTION AND APPLICATION OF AIRBORNE GAMMA-RAY SPECTROMETER CALIBRATION PADS — THAILAND

R.L. GRASTY

1987

© Minister of Supply and Services Canada 1987

Available in Canada through

authorized bookstore agents and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Canada K1A 0S9

and from

Geological Survey of Canada offices:

601 Booth Street
Ottawa, Canada K1A 0E8

3303-33rd Street N.W.
Calgary, Alberta T2L 2A7

A deposit copy of this publication is also available
for reference in public libraries across Canada

Cat. No. M44-87/10E Canada: $5.00
ISBN 0-660-12570-6 Other countries: $6.00

Price subject to change without notice

Cover

See page 16, Figure 14 for details.

Critical Reader

M. Matolin
Charles University
Prague, Czechoslovakia

Original manuscript submitted 1986-10
Final version approved for publication 1987-01

CONTENTS

Foreword/Avant-propos: A.G. Darnley
1 Abstract/Résumé
1 Introduction
1 Purpose of calibration pads
4 Design considerations
4 Number of pads
5 Ideal concentrations
6 Dimensions
9 Particle size
11 Pad construction
11 Site selection
11 Material selection
13 Material requirements
13 Preparation of materials
15 Construction procedures
18 Pad concentrations
19 Calibration – theory
20 Calibration – practice
20 Sealing of pads
21 Dead-time considerations
23 Pulse pile-up considerations
23 Recommended calibration procedure
24 Discussion
24 Comparative study
25 Environmental considerations
26 Radon loss from the uranium pad
27 Recommendations for pad construction
28 Acknowledgments
28 References

Appendices

30 A. Calibration pads – procedure
30 B. Dead-time determination – procedure
31 C. Dead-time determination – results
32 D. Calibration pads – results
33 E. Computation of calibration factors (matrix method)
34 F. Hewlett-Packard 15C computer program to calibrate a spectrometer on the Thailand pads

Tables

2 1. Spectral windows used to measure gamma rays
6 2. Ideal pad concentrations
6 3. Concentrations of Borlange pads – Sweden
6 4. Response of circular sources of different radii (detector height - 1 m)
8 5. Response of sources of different thickness (detector at ground level)
9 6. Concentrations of some calibration pads
9 7. Effect of particle size on the analysis of 400 g concrete samples of 100 ppm uranium
10 8. A comparison of the experimental and theoretical errors in the analyses of concrete samples from the Portable Calibration Facilities, Bells Corners, Ottawa, Canada
12 9. Analysis of pad material
12 10. Mineral composition of construction material
13 11. Materials acquired
13 12. Grain size analysis of construction material
15 13. Analysis of U-500 and T-1000 concentrates
18 14. Total materials used in pad construction
18 15. Portable gamma-ray spectrometer homogeneity tests on the pads
19 16. Density and porosity of the Thailand pads
20 17. Analysis of Thailand concrete samples
20 18. Assigned pad concentrations
21 19. The apparent effect of covering the uranium pad with plastic sheet
21 20. Variations of the uranium window count rate on the blank pad
22 21. The apparent uranium sensitivity of the GR-410 portable spectrometer before and after the pads were sealed
22 22. The effect of dead-time corrections on the calibration of an airborne spectrometer on the Thailand pads
23 23. The effect of pulse pile-up on the calibration of an airborne spectrometer on the Thailand pads
25 24. Errors associated with the calibration of a GR-410 portable spectrometer at various calibration facilities
26 25. Measured and calculated exposure rate on the Thailand pads

Figures

2	1.	An airborne gamma-ray spectrum showing the four windows
3	2.	A potassium spectrum obtained from an airborne system on the calibration pads at Grand Junction, Colorado
4	3.	A uranium spectrum obtained from an airborne system on the calibration pads at Grand Junction, Colorado
5	4.	A thorium spectrum obtained from an airborne system on the calibration pads at Grand Junction, Colorado
7	5.	Response of circular sources of different radii
8	6.	Response of infinite slabs of different thickness
10	7.	U-Tapao airfield showing ground profile and pad location
11	8.	Scintillometer profile used to select pad location
14	9.	A drum of U-500 uranium concentrate prepared by mixing uranium ore with fine silica sand
14	10.	Drums of U-500 concentrate with the drum used to ship the Canadian uranium ore to Thailand
15	11.	The full drum of silica sand which initially resulted in an inhomogeneous U-500 uranium concentrate
16	12.	The warehouse with the bags of sand, cement and feldspar
16	13.	Loading a bag of sand into a cement truck
16	14.	The pouring of the pads showing the wooden forms
16	15.	Spreading the sand-cement mix across the pad
17	16.	Measuring the U-500 uranium concentrate into plastic buckets
17	17.	Loading the U-500 uranium concentrate into a cement truck
18	18.	Checking the homogeneity of the pads with a portable gamma-ray spectrometer
19	19.	Sampling the sand-cement mix as it was being poured
19	20.	Metal sample cans for gamma-ray analyses and plastic containers for density and porosity
21	21.	Sealing the uranium pad with a plastic sheet
23	22.	A helicopter showing a detector box near the edge of the pad
24	23.	Painting a line on the pads to locate the helicopter skid
25	24.	Profile of the exposure rate measured over the calibration pads
26	25.	An electron backscattered image of a relatively fresh uraninite grain
27	26.	An electron backscattered image of a partially decomposed uraninite grain

Foreword

It may be of some interest to explain the chain of events which has led to the Geological Survey of Canada being involved in the construction of radiometric calibration facilities in Thailand.

Airborne geophysical surveys have been part of GSC's ongoing activities since 1947, and over the course of 40 years considerable expertise has been acquired, as a result of in-house R&D, annual survey operations, and close association with the development of the Canadian air survey industry. For 25 years the Geological Survey of Canada has acted on behalf of the Canadian International Development Agency as technical advisor in the planning and conduct of airborne geophysical surveys by Canadian contractors in many countries in Africa, Latin America and Asia.

GSC first become involved with airborne gamma-ray spectrometry in 1966. It was recognized from the beginning that although the measurements depended upon physical phenomena, the main significance, from a geological point of view, lay in the geochemical information, and the ability to produce results in terms of ground-level elemental concentrations of K, U and Th. In order to equate physical measurements to chemical concentrations it was necessary to find a method to interlink laboratory standards to airborne data. This entailed a number of steps, the most elaborate of which was the design and construction of a set of concrete calibration pads, spiked with known amounts of potassium, uranium and thorium. Used in conjunction with a calibrated flight-test range several kilometres in length, these made it possible for any sensitive, stable gamma-ray spectrometer system carried in an aircraft to provide a measurement of ground-level radioelement concentrations. The first pads were constructed in Ottawa in 1968, enabling the first geochemical maps made from the air to be published in 1971.

The Geological Survey of Canada became a participant in the airborne survey of Thailand as the result of an approach in 1982 by the Asian Development Bank to the Canadian International Development Agency. It followed from a proposal for mineral resources development submitted to the bank by the Royal Thai Government Department of Mineral Resources. Early in 1983 GSC advisors were asked to provide detailed specifications for a comprehensive multi-sensor airborne geophysical survey of the whole of Thailand, approximately 450 000 km^2. This work was to be financed by an Asian Development Bank loan to the Royal Thai Government, and the participation of GSC advisors was to be supported by the Canadian International Development Agency. The RTG Department of Mineral Resources issued an international call for tenders for the execution of the survey, and a contract was subsequently awarded to Kenting Earth Science Ltd. of Ottawa. The contractor was required to provide calibration facilities in Thailand to enable the gamma-ray spectrometer surveys, which formed a major component of the airborne work, to be carried out according to GSC specifications. The provision of calibration facilities is not an activity which a geophysical contractor is equipped to undertake, and so there arose a need for technology transfer between government and industry, Canada and Thailand, involving GSC, DMR and Kenting. There was one other participant in Ottawa, the Canada Centre for Mineral and Energy Technology, who gave assistance in the preparation of the Beaverlodge uranium ore used for the uranium spikes. The potassium and thorium spikes were prepared in Thailand.

Avant-propos

Il est peut-être de quelqu'intérêt d'expliquer le cours des évènements qui a fait que la Commission géologique du Canada soit impliquée dans la construction d'outillages de calibration radiométrique en Thaïlande.

Les levés géophysiques aériens se situent parmi les travaux courants de la CGC depuis 1947 et pour plus de quarante ans une considérable expérience a été acquise à partir de résultats obtenus par le développement du R&D, des levés annuels et de l'étroite association avec l'industrie canadienne spécialisée en levés aériens. Depuis vingt-cinq ans, la Commission géologique du Canada joue un rôle actif à l'Agence canadienne de développement international comme conseiller technique dans la planification et la conduite de levés géophysiques aériens menés par les entrepreneurs canadiens dans plusieurs pays d'Afrique, d'Amérique latine et d'Asie.

Pour la première fois, c'est en 1966 que la CGC fut impliquée dans la spectrométrie aérienne à rayons gamma. Il fut reconnu au tout début que même si les mesures sont fonctions des phénomènes physiques, la principale signification, d'un point de vue géologique, se trouve au niveau de renseignements provenant de données géochimiques et de la facilité d'obtenir des résultats suivant les concentrations dans le sol de K, U et Th. Afin d'obtenir des mesures physiques adéquates pour les concentrations d'éléments chimiques, il fut nécessaire de trouver une méthode qui soit capable d'unifier les normes de laboratoire aux données obtenues de levés aériens; ceci implique un certain nombre d'étapes; la plus élaborée d'entre elles a été la conception et la construction d'un jeu de blocs de calibration bétonnés contenant des quantités déterminées de potassium, d'uranium et de thorium servant de repaires. Mis à l'essai suivant un calibrage donné au cours de vols sur des distances de plusieurs kilomètres, on constate, aux résultats de ces essais, la performance, pour toute la gamme de sensibilité, d'un système stable spectrométrique à rayons gamma monté sur avion dans le but de mesurer les concentrations de radioéléments dans le sol. Les premiers blocs de calibration ont été construits à Ottawa en 1968; ce qui permit l'apparition des premières cartes géochimiques en 1971 dressées à partir de données provenant de levés aériens.

La Commission géologique du Canada est devenue un participant des levés aériens en Thaïlande par un contact, en 1982, avec la Banque de développement de l'Asie par l'intermédiaire de l'Agence canadienne de développement international. Cette approche a été favorisée par une demande pour le développement des ressources minérales soumise à la Banque de l'Asie par le ministère des Ressources minérales du gouvernement thaïlandais. Tôt en 1983, les conseillers de la CGC, à la demande de ce ministère, fournissent des avis pertinents pour un levé géophysique multi-capteur aérien à l'étendue du territoire thaïlandais, environ 450 000 km^2. Ce travail a été financé par un prêt de la Banque de développement de l'Asie au gouvernement thaïlandais, et la participation des conseillers de la CGC l'a été par l'Agence canadienne de développement international. Le ministère des Ressources minérales de Thaïlande émis des appels d'offre pour permettre la réalisation de ces levés; cette démarche a abouti à un contrat avec la Kenting Earth Science Ltd. d'Ottawa. L'entrepreneur eut la responsabilité de fournir l'outillage de calibration en Thaïlande afin de réaliser les levés spectrométriques à rayons gamma, lesquels constituaient la partie la plus importante de l'ensemble des levés devant être effectués suivant les modalités d'exécution de la CGC. L'apport d'outillage de calibration n'est pas normalement en la possession du contracteur de levés géophysiques, ce qui l'oblige, dans bien des cas, à une entraide technologique entre l'entreprise privée et l'État; ce qui impliquait, d'une part, le Canada et la Thaïlande, par l'entremise de la CGC et le ministère des Ressources minérales thaïlandais, d'autre part, la Kenting Ltd. Il y eut un autre participant d'Ottawa, le Centre canadien de la technologie minérale et énergétique, qui apporta son aide dans la préparation des minérais d'uranium de Beaverlodge utilisés pour les repaires d'uranium. Les repaires de potassium et de thorium furent préparés en Thaïlande.

The following detailed account of calibration pad construction is presented partly to record what has been accomplished for this particular project, and partly to revise and supplement what has been previously written on the subject. It will serve as a manual for future pad construction elsewhere. Airborne gamma-ray spectrometry is now firmly established as a standard airborne mapping tool applicable in many parts of the world. This requires the existence of the type of calibration facilities which have been created in Thailand through the initiative of the Mineral Resources Development project. The Geological Survey of Canada is pleased to have had the opportunity to work with the Department of Mineral Resources, Bangkok, in this co-operative practical endeavour.

A.G. Darnley
Director
New Technology and
International Programs

La description détaillée de la construction des blocs de calibration est exposé dans ce rapport technique en partie pour reconnaitre ce qui a été accompli pour ce projet et, aussi, pour faire une revision et apporté des connaissances nouvelles à ce qui a été fait à ce sujet. Ce rapport servira comme manuel pour la construction éventuelle de blocs de calibration où la demande se fera sentir. La spectrométrie aérienne à rayons gamma est maintenant solidement établie comme un outil aéroporté normalisé d'une application universelle. Ceci requière l'existence d'un type d'outillage de calibration suivant les normes adoptées par le ministère du Développement des Ressources minérales thailandais pour qui ce genre d'outillage a été conçu pour la réalisation du projet. La Commission géologique du Canada est heureuse d'avoir eu la chance de participer conjointement avec ce ministère. C'est un bel exemple de coopération scientifique et technique avec un pays du Sud-Est asiatique.

Le directeur, Nouvelle technologie
et programmes internationaux
A.G. Darnley

THE DESIGN, CONSTRUCTION AND APPLICATION OF AIRBORNE GAMMA-RAY SPECTROMETER CALIBRATION PADS IN THAILAND

Abstract

Four concrete pads 7.6 x 7.6 m (25 x 25 ft.) by 0.5 m (18 in.) thick were constructed in Thailand for calibrating airborne gamma-ray spectrometers. They comprised a low radioactivity background pad, a potassium pad, a uranium pad and a thorium pad.

The background pad was constructed of masonry sand and cement and the uranium and thorium pads with a small quantity of uranium and thorium ore added to the same background matrix. The potassium pad was constructed from feldspar and cement. The uranium ore, from Canada, was in radioactive equilibrium and a low emanator of radon. The thorium ore, a separated monazite beach sand, and the feldspar were both obtained in Thailand.

A few months after construction, the gamma-ray activity of the uranium pad was found to fluctuate due to loss of radon. Its gamma-ray activity was then stabilized through the use of a flexible waterproof paint. One year after sealing, the uranium pad was again found to be losing radon.

The concentrations of the four pads are:

	K (%)	eU (ppm)	eTh (ppm)
Background	0.25 ± 0.01	0.91 ± 0.03	2.86 ± 0.05
K Pad	6.18 ± 0.06	1.46 ± 0.05	1.16 ± 0.06
U Pad	0.25 ± 0.01	16.21 ± 0.27	2.86 ± 0.05
T Pad	0.25 ± 0.01	2.54 ± 0.05	37.31 ± 0.42

Résumé

On a construit en Thaïlande quatre blocs en béton de 7,6 x 7,6 m (25 x 25 pi) et de 0,5 m (18 po) d'épaisseur en vue de l'étalonnage de spectromètres à rayons gamma aéroporté. Ces blocs consistaient en un bloc de fond de faible radioactivité, un bloc de potassium, un bloc d'uranium et un de thorium.

Le bloc de fond a été construit avec du sable et du ciment à maçonner, et les blocs d'uranium et de thorium ont été obtenus en ajoutant une petite quantité de minerai d'uranium et de thorium à la même matrice de fond. Le bloc de potassium a été fabriqué avec du feldspath et du ciment. Le minerai d'uranium, provenant du Canada, était en équilibre radioactif et dégageait peu de radon. Le minerai de thorium, un sable littoral à monazite obtenu par séparation, et le feldspath provenaient tous deux de la Thaïlande.

Quelques mois après la construction, on a trouvé que l'activité gamma du bloc d'uranium variait en raison des pertes de radon. On a stabilisé l'activité gamma en utilisant une peinture hydrofuge flexible. Un an après avoir appliqué ce revêtement d'étanchéité, on a constaté que le bloc d'uranium dégegeait encore du radon.

Les concentrations des quatre blocs sont les suivantes:

	K (%)	eU (ppm)	eTh (ppm)
Bloc de fond	0,25 ± 0,01	0,91 ± 0,03	2,86 ± 0,05
Bloc de K	6,18 ± 0,06	1,46 ± 0,05	1,16 ± 0,06
Bloc d'U	0,25 ± 0,01	16,21 ± 0,27	2,86 ± 0,05
Bloc de Th	0,25 ± 0,01	2,54 ± 0,05	37,31 ± 0,42

INTRODUCTION

On 6, 7 July 1984 four airborne gamma-ray spectrometer calibration pads were constructed in Thailand, at U-Tapao Airport, on the Gulf of Thailand, approximately 150 km southeast of Bangkok. This calibration facility was constructed by Kenting Earth Sciences of Canada as part of their contract with the Thai Department of Mineral Resources (DMR) for an airborne geophysical survey of Thailand.

As part of an agreement between the Canadian International Development Agency (CIDA) and DMR, the Geological Survey of Canada (GSC) provided technical advice to DMR on all aspects of the airborne survey program. Following a request by DMR, GSC agreed to supervise the construction of the calibration facilities at U-Tapao. This report describes the design, and construction of these pads and their application to the calibration of airborne gamma-ray spectrometers.

PURPOSE OF CALIBRATION PADS

Figure 1 shows a typical gamma-ray spectrum recorded at a survey altitude of 120 m using a 50 L sodium-iodide detector system. Gamma-ray peaks at 2.62 MeV, 1.76 MeV and 1.46 MeV representing thallium-208 in the thorium decay

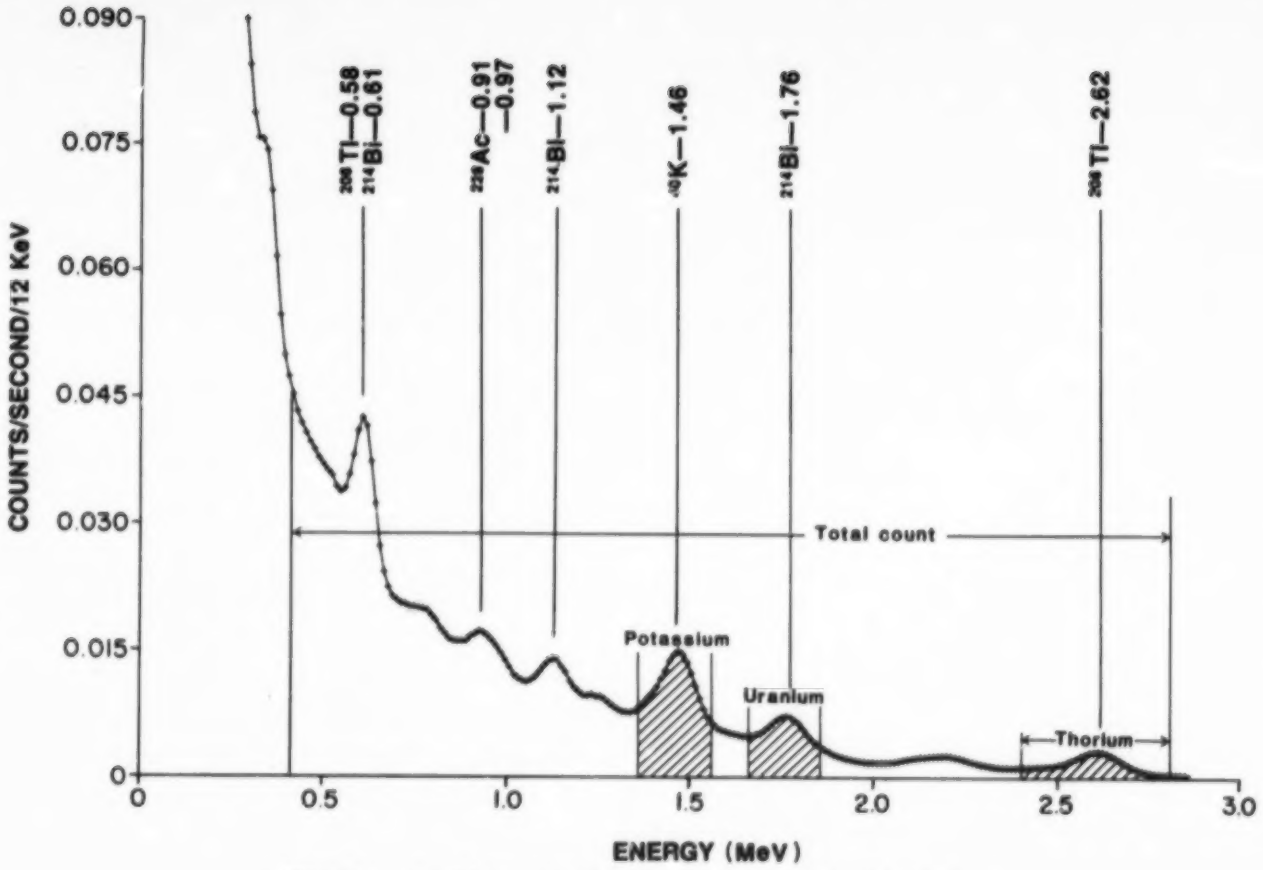

Figure 1. An airborne gamma-ray spectrum showing the four windows.

series, bismuth-214 in the uranium decay series and potassium-40 can be readily distinguished. These particular gamma-ray emissions have been generally accepted as the most suitable for the measurement of thorium, uranium and potassium, because they are relatively abundant at ground level and their energies are high enough that they are not appreciably attenuated at survey altitudes up to 120 m. The energy windows used to monitor these gamma-rays for the Thailand survey are shown in Table 1 and are those recommended by the International Atomic Energy Agency (IAEA, 1976). The total count window is useful in geological mapping since it reflects general lithological variations (Pitkin, 1968).

In the Thailand airborne program, three aircraft were carrying out gamma-ray spectrometer surveys. The three aircraft were a fixed-wing Islander and two Bell-412 helicopters, each of which had an instrument package of sodium iodide detectors with a volume of approximately 50 L. In order to compare the results from the three systems properly a standardized method of calibration and reporting must be followed. Following the recommendations of the International Atomic Energy Agency (IAEA, 1976), the contract between Kenting and the Thai government specified that the results from the three spectrometers were to be reported in terms of ground concentrations of potassium, uranium and thorium.

In calibrating an airborne gamma-ray spectrometer so that the count rates in the three radioelement windows may be converted to ground concentrations, three basic sets of calibration constants are required. They are:

1. the system sensitivities,
2. the height attenuation coefficients and
3. the stripping ratios.

The system sensitivities are normally determined from flights over an airborne test strip whose radioelement concentrations are measured on the ground at the time of the calibration flights using a portable gamma-ray spectrometer. The three sensitivities which are determined at the nominal survey altitude are normally expressed as:

1. counts per second in the potassium window per per cent potassium,
2. counts per second in the uranium window per ppm uranium,
3. counts per second in the thorium window per ppm thorium.

Table 1. Spectral windows used to measure gamma rays

Element Analyzed	Isotope Used	Gamma ray Energy (MeV)	Energy Window (MeV)
Potassium	^{40}K	1.46	1.37 - 1.57
Uranium	^{214}Bi	1.76	1.66 - 1.86
Thorium	^{208}Tl	2.62	2.41 - 2.81
Total Count			0.41 - 2.81

The height attenuation coefficients are used to correct the window count rates for deviations from the planned survey altitude. It has been found by experiment that in the range of altitudes normally encountered in airborne survey operations, the count rate (N) in each window can be adequately represented by a simple exponential expression of the form:

$$N = Ae^{-\mu h} \qquad (1)$$

where A and μ are constants and h is the altitude of the aircraft above the ground (Darnley et al., 1968; Kogan et al., 1971; Burson, 1973). The exponential height correction parameter μ is determined for each of the three radioelements by monitoring their respective window count rates over the test strip at several different altitudes. The total count exponential height attenuation coefficient is measured at the same time.

The stripping ratios provide information on the shape of the gamma-ray spectrum of the three radioelements. This information is determined from measurements on large concrete calibration sources with known concentrations of the three radioelements. Figures 2, 3 and 4 show the potassium, uranium and thorium gamma-ray spectram for a detector package of 16.8 L recorded on the calibration pads at Grand Junction, Colorado (Ward, 1978). Due to Compton scattering in the ground, some counts from 2.62 MeV thallium-208 photons from a pure thorium source are recorded in the lower energy potassium and uranium windows. Counts in these lower energy windows also arise from the incomplete absorption of 2.62 MeV photons in the detector or from other lower energy gamma-ray photons in the thorium decay series. Similarly counts will be recorded in the lower energy potassium windows from a pure uranium source and can also appear in the high energy thorium window due to high energy gamma-ray photons of bismuth-214 in the uranium decay series. Due to the poor resolution of sodium iodide detectors, counts can also be recorded in the uranium channel from a pure potassium source.

The stripping ratios are the ratios of the counts detected in one window to those in another window from a pure source of potassium, uranium and thorium. The stripping ratios alpha, beta, gamma, a, b, and g are defined as:

alpha: - the ratio of the counts detected in the uranium window to those detected in the thorium window from a pure thorium source.

beta: - the ratio of the counts detected in the potassium window to those detected in the thorium window from a pure thorium source.

gamma: - the ratio of the counts detected in the potassium window to those detected in the uranium window from a pure uranium source.

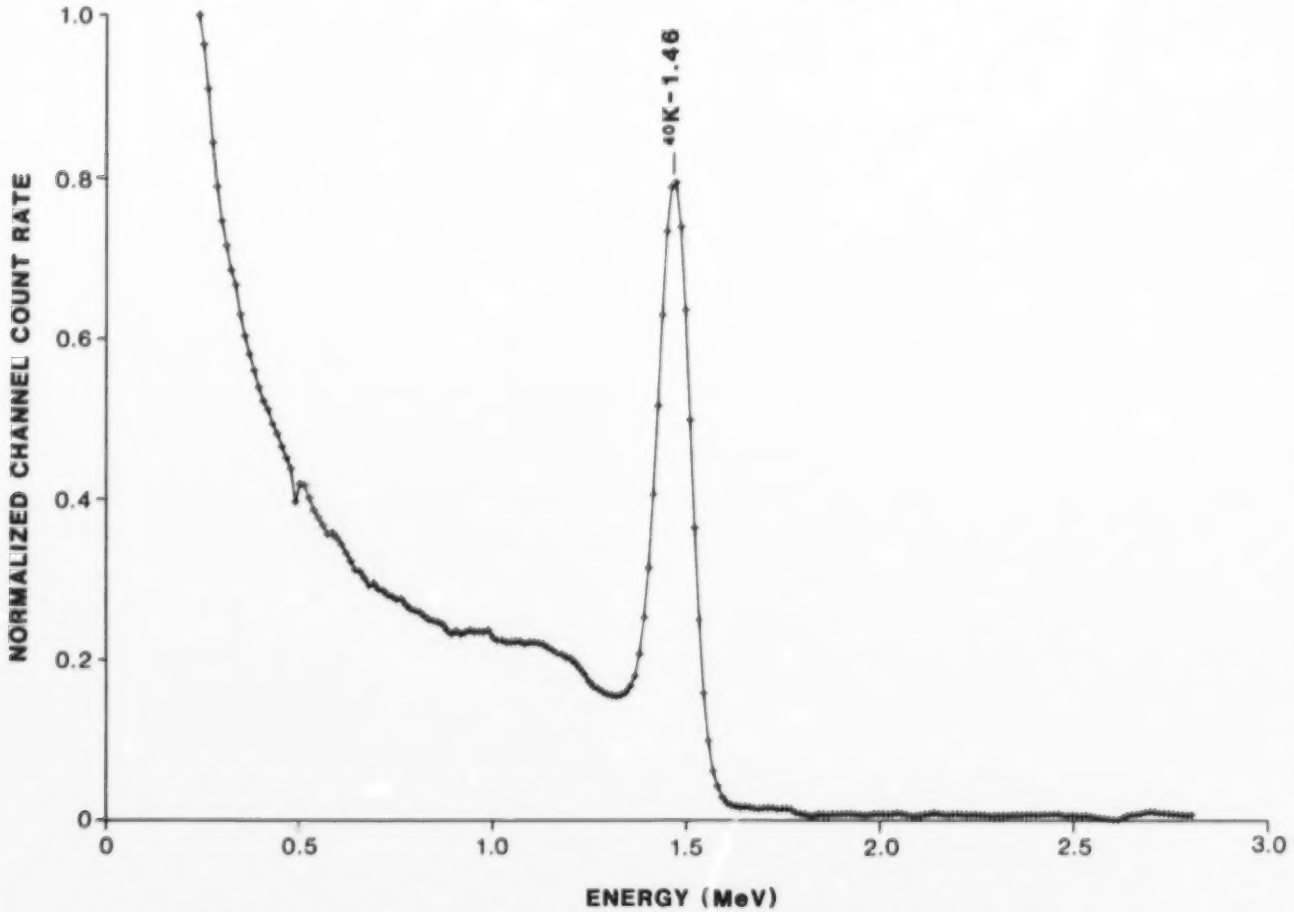

Figure 2. A potassium spectrum obtained from an airborne system on the calibration pads at Grand Junction, Colorado.

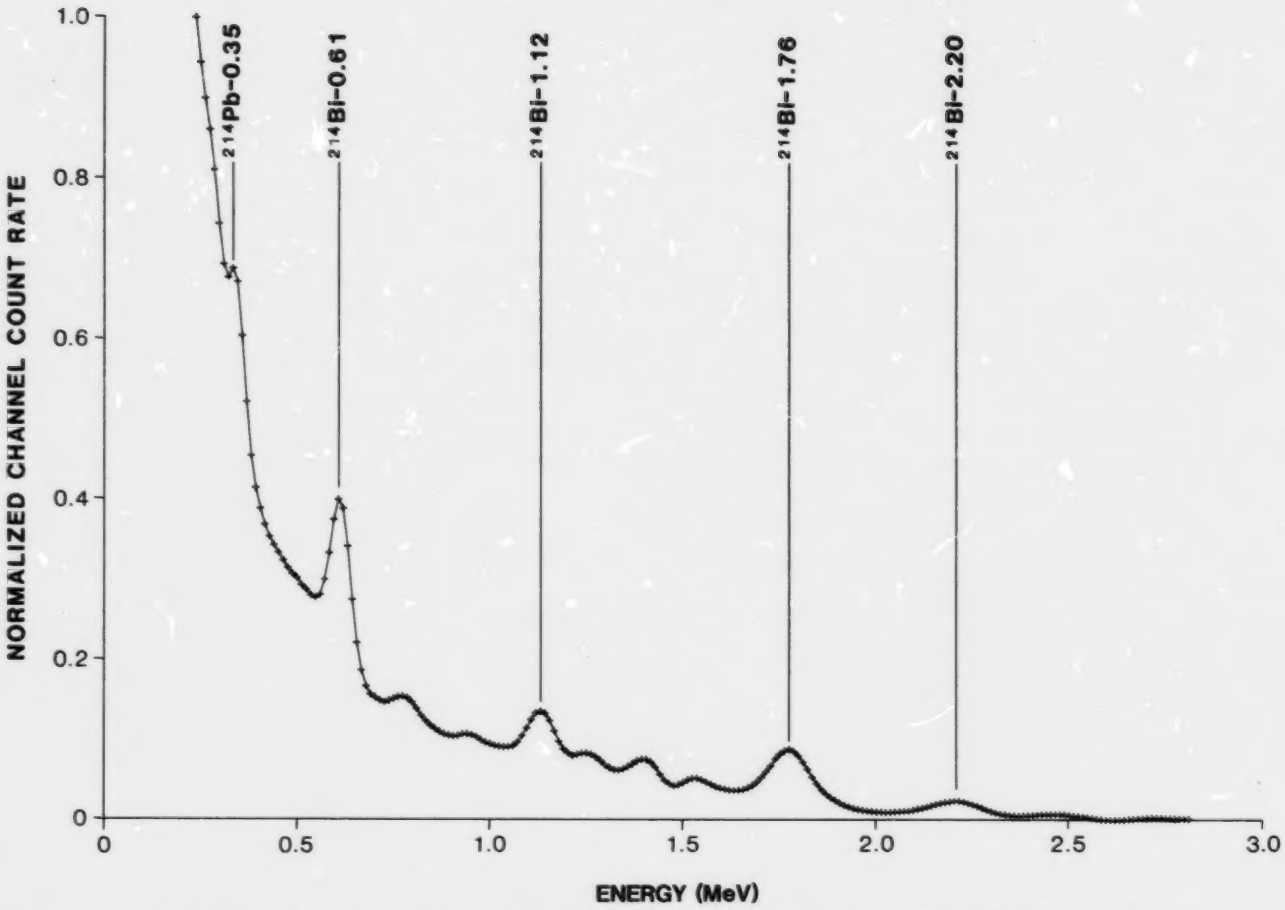

Figure 3. A uranium spectrum obtained from an airborne system on the calibration pads at Grand Junction, Colorado.

a: - the ratio of the counts detected in the thorium window to those detected in the uranium window from a pure uranium source.

b: - the ratio of the counts detected in the thorium window to those detected in the potassium window from a pure potassium source. For the windows used in the Thailand survey, shown in Table I, b has a value of zero.

g: - the ratio of the counts detected in the uranium window to those detected in the potassium window from a pure potassium source.

The airborne calibration pads are used to derive these stripping ratios so that the gamma-ray count rate originating from each of the three radioelements can be determined. They serve only one aspect of the airborne gamma-ray spectrometer calibration process.

DESIGN CONSIDERATIONS

Number of pads

Much experience has been gained on the construction and use of airborne gamma-ray calibration facilities since they were first built in Canada in 1968. Current thinking has also changed since the IAEA Technical Report on Calibration was published in 1976 (IAEA, 1976).

The IAEA report recommended only three calibration pads be constructed for airborne spectrometers. One to be spiked with uranium, one with thorium and the third (blank) serving as a background to remove the effects of the surrounding soil, decay products of radon in the air, cosmic radiation and the radioactivity of the aircraft. With these pads the stripping ratios alpha, beta, gamma and "a" could be determined since the pads could provide a pure thorium and uranium spectrum. No potassium pad was recommended since at that time it was considered that there was negligible interference from a potassium spectrum into the uranium and thorium windows i.e. "b" and "g" were effectively zero. However, in practice, due to the difficulty of aligning the gamma-ray spectra from a large number of detectors in a high sensitivity system, a small percentage of potassium gamma-rays can be detected in the uranium window. These potassium gamma-rays can be a significant fraction of those originating from the uranium decay series due to the abundance of potassium gamma-rays emitted by normal rocks and soils. The measurement of "g" also serves as a useful check on the detector system since any gain change or decrease in energy resolution can result in an increase in the value of "g".

With no potassium pad, the potassium sensitivity of an airborne system cannot be determined on the pads. If the background pad does not have exactly the same potassium concentration as the thorium or uranium pad, it is impossible

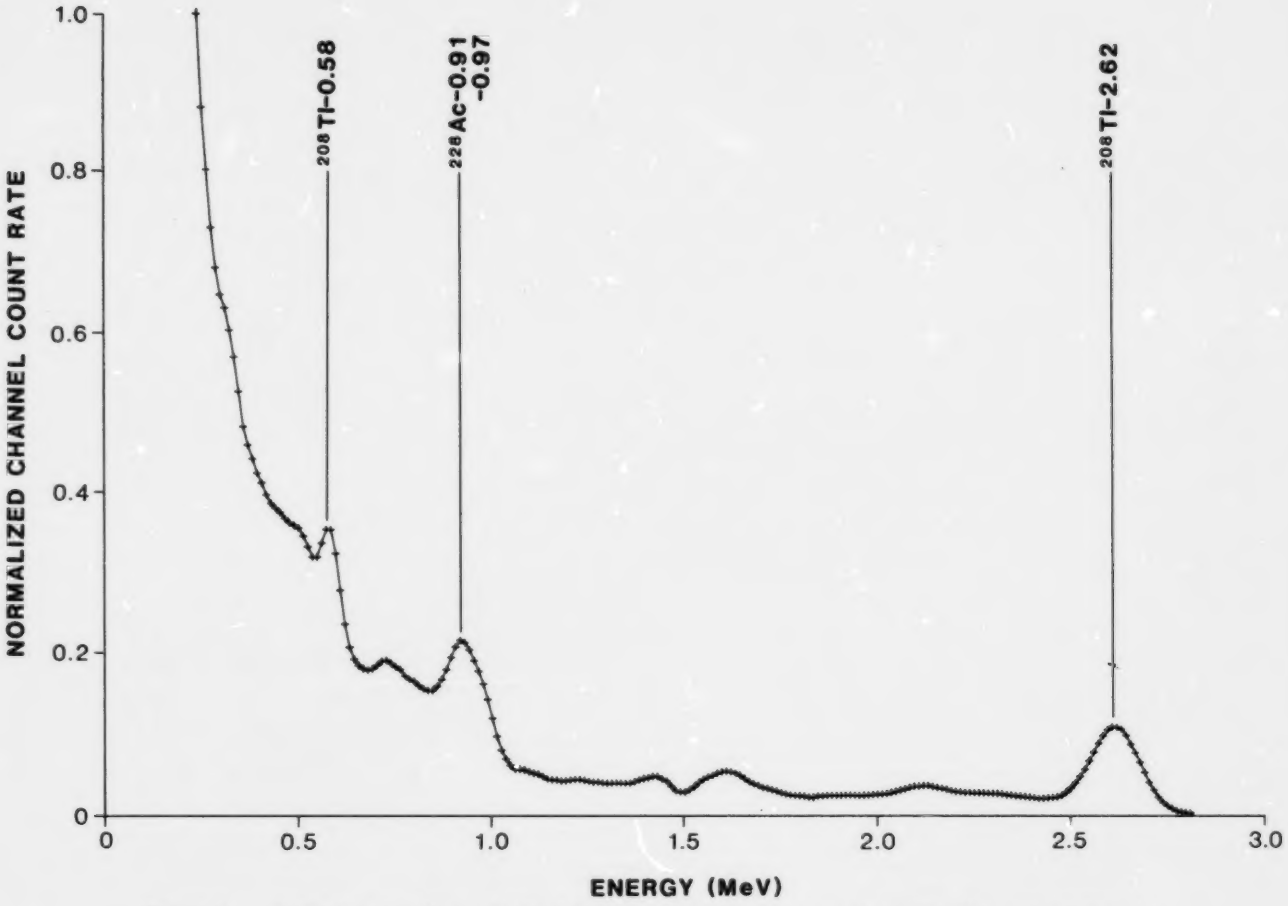

Figure 4. A thorium spectrum obtained from an airborne system on the calibration pads at Grand Junction, Colorado.

to obtain a pure uranium or thorium spectrum by subtraction of the 'blank' spectrum. The potassium contribution to the thorium and uranium spectra is therefore impossible to determine and the stripping ratios beta and gamma cannot be evaluated. A potassium pad is also necessary to calibrate the portable gamma-ray spectrometer used to monitor the radioelement concentration of the test strip. Since no facilities were available in Thailand for calibrating portable spectrometers, it was advantageous if the aircraft calibration pads could be used to calibrate portable spectrometers. For these reasons it was considered necessary to construct a potassium pad.

With four pads (a potassium, uranium, thorium and a background pad), all the stripping ratios of a gamma-ray spectrometer at ground level can be determined uniquely. Any additional pad of mixed composition can be used to provide a check on the calibration constants as was originally intended for the pads at Grand Junction, Colorado. Alternatively measurements on the mixed pad can be incorporated into the analysis procedure to derive better estimates of the stripping ratios. However, a mixed pad has several practical disadvantages which can cause analytical problems in the calibration procedure.

With pure pads the accuracy of the stripping ratios do not depend on the accuracy of the measured pad concentrations, since by definition they are the ratio of the counts in the respective windows from a pure source. For a mixed pad, the concentrations of all the radioelements must be known as accurately as possible. Any errors in the concentrations will affect the accuracy to which the stripping ratios can be determined.

Any equipment dead time due to the relatively high count rate expected on the pads will decrease the true count rates. With pure pads this decrease has only a minor effect on the stripping ratios if no dead-time correction is applied because all the window count rates are decreased proportionally. A different dead-time on the potassium and uranium pad will have little effect on the stripping ratios derived from these pads provided the background contribution is small. However, on a mixed pad, the window sensitivity of each radioelement may be quite different from that on a pure pad if the dead-times are different. Consequently, erroneous stripping ratios may result if mixed pads are used and no dead-time correction or an incorrect dead-time correction is applied. For these reasons, it was felt that a mixed pad would serve no useful purpose in the calibration procedure provided that pads were constructed which were relatively pure in their respective radioelements.

Ideal concentrations

The exact concentrations of the pads are somewhat arbitrary. They need to be sufficiently radioactive to essentially eliminate errors in the stripping ratios from counting statistics, but at the same time the count rate should not be so high that dead time becomes a significant problem.

It was considered important that potential problems due to electronic dead time be minimized by constructing the three single radioelement pads so that the total count rate and the associated dead-time was approximately the same on the potassium, uranium and thorium pads. From a study of gamma-ray spectra recorded on the Grand Junction calibration pads, it was found that this could be achieved if the concentrations of the pads were in the proportions of 2% K to 5 ppm eU to 10 ppm Th. Since it is difficult with normal material to manufacture a potassium pad with a concentration higher than about 8%, the ideal concentrations (Table 2) are about as high as can be reasonably achieved and yet still be in the required ratio to produce similar total count rates on all three radioactive pads. These uranium and thorium concentrations are also those recommended by the IAEA (1976). The concentrations of the airborne calibration pads at Borlange, Sweden constructed by the Swedish Geological Survey (Table 3) also compare favourably with those recommended in this report (Løvborg, 1984).

Dimensions

For an airborne gamma-ray spectrometer system, the detectors are normally mounted in the body of the aircraft. When the aircraft is on the ground, the detectors are typically about 1 m above the surface of the ground.

The detector count rate (N) from an infinitely thick circular source subtending an angle 2ϕ at the detector is given by

$$N = A \left[E_2 (\lambda h) - \cos \phi \, E_2 \left(\frac{\lambda h}{\cos \phi} \right) \right] \qquad (2)$$

where h is the height of the detector above the surface of the ground, λ is the linear attenuation coefficient of gamma-rays in the air and A is a constant (King, 1912).

The E_2 function is known as the exponential integral of the second kind and in Russian literature is often referred to as the King function. $E_2 (\lambda h)$ is given by

$$E_2 (\lambda h) = \int_1^{\infty} \frac{e^{-\lambda h x}}{x^2} \, dx \qquad (3)$$

From equation (2) it can readily be calculated that the radiation detected from a circular source compared to the total radiation originating from an infinite source, expressed as a percentage P, is given by

$$P = 100 \left[\frac{E_2 (\lambda h) - \cos \phi \, E_2 (\lambda h / \cos \phi)}{E_2 (\lambda h)} \right] \qquad (4)$$

These results are illustrated in Figure 5 and also tabulated in Table 4 for thorium gamma-rays of energy 2.62 MeV with a detector at a height of 1 m above the surface of the source. Løvborg (1984) has shown that the theoretical equation (4) can be approximated by the formula:

$$P = 100 (1 - h/R) \qquad (5)$$

where R is the radius of the circular source.

The results presented in Table 4 show that it is impractical to build calibration pads which are effectively infinite in size for an airborne system with a detector at a typical elevation of 1 m above the ground. This is the principal reason why the pads are only used to derive the stripping ratios and not the sensitivites of an airborne system.

In calculating the stripping ratios using the calibration pads it is important that the background radiation from the materials surrounding the pads should be the same on all four pads as it can then be removed from the measurements on the three radioelement pads by subtracting the background or blank pad readings. In order to minimize errors due to counting statistics and possible differences in the background radiation on the different pads, the background contribution should be reduced as much as possible by making the pads as large as practically possible.

There are also good theoretical and practical reasons why the pads should be as large as possible. With a small pad, the radiation detected is more sensitive to changes in the position of the detector compared to a large pad. The response of large volume detector arrays used in airborne operations is dependent on the angle the radiation strikes the detector. For the GSC system, the stripping ratio α for a point source of thorium varies from 0.22 to 0.27 depending on the position of the soure in relation to the detectors. In an airborne survey operation, the gamma radiation strikes the detector at all angles of incidence. The pads should therefore provide a source of radiation which best simulates the airborne situation. Clearly this cannot be achieved with pads of small dimension.

Table 2. Ideal pad concentrations

	K (pct)	eU (ppm)	eTh (ppm)
Blank Pad	0	0	0
K Pad	8	0	0
U Pad	0	20	0
T Pad	0	0	40

Table 3. Concentrations of Borlange pads - Sweden

	K (pct)	eU (ppm)	eTh (ppm)
Blank Pad	0.40	1.53	2.4
K Pad	7.50	1.03	1.3
U Pad	0.70	24.8	2.6
T Pad	0.60	3.58	49.1

Table 4. Response of circular sources of different radii (detector height 1 m)

Radius of circular source (m)	Percentage of infinite source
0.5	10.8
1.0	30.0
1.5	45.5
2.0	56.5
2.5	64.2
3.0	69.8
3.5	74.0
4.0	77.3
4.5	79.8
5.0	81.9
6.0	85.1
7.0	87.4
8.0	89.1
9.0	90.5
10.0	91.5
15.0	94.7
20.0	96.3

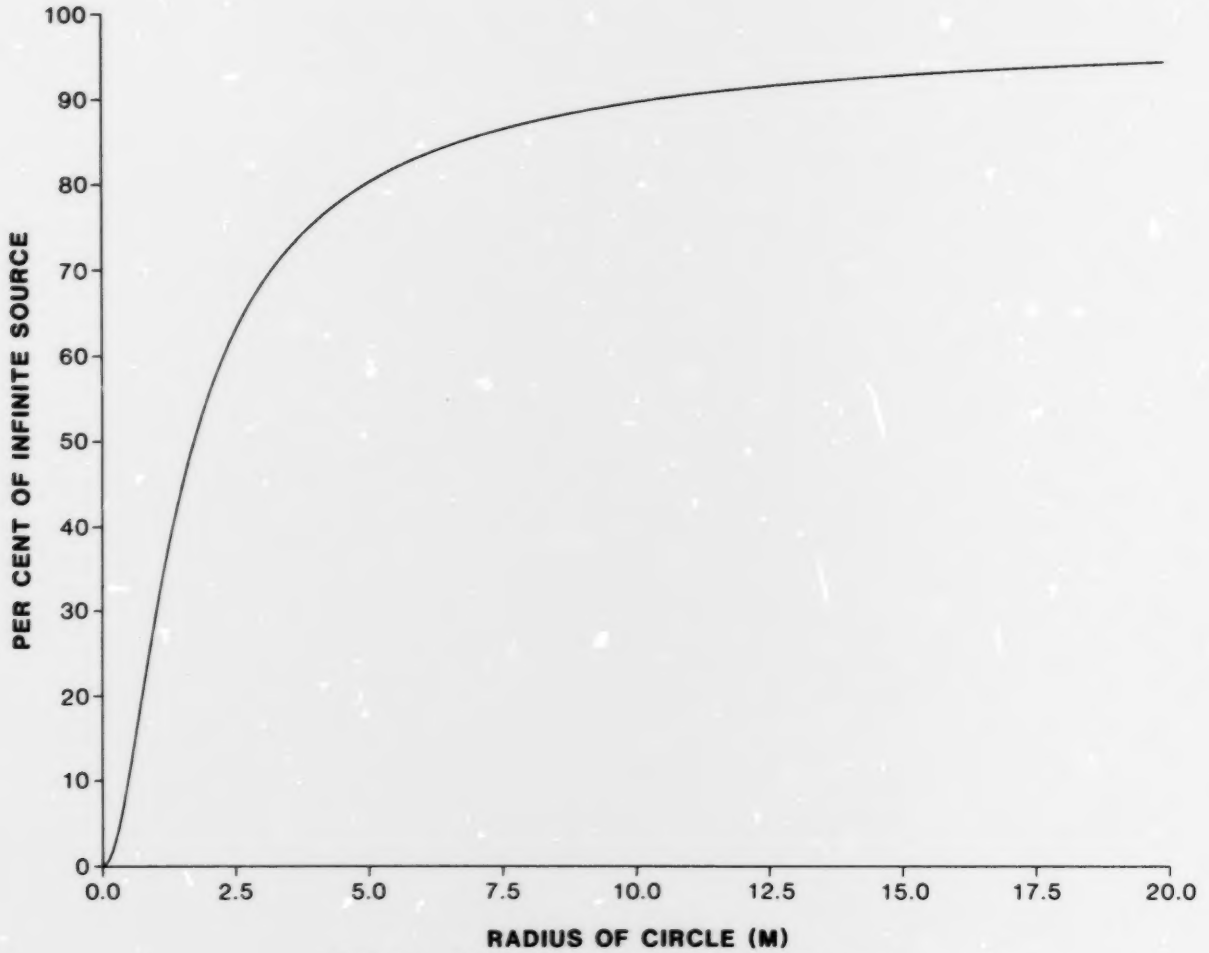

Figure 5. Response of circular sources of different radii.

The IAEA (1976) recommended that the pads should have a minimum diameter of 8 m. Table 4 shows that with this size, the count rates on the pads have reached 77 per cent of the infinite source value. By doubling the area of the pads and the associated costs of the materials the diameter will increase to 11.3 m ($8\sqrt{2}$). However, the percentage of the infinite source will only increase to 84 per cent. For practical reasons, it was decided to construct calibration pads which were 7.6 m (25 ft.) square. The pads then cover an area which is somewhat greater than that recommended by the IAEA and will give slightly higher count rates. With pads of these dimensions, background variations on the four pads from the surrounding ground will be minimal, the radiation striking the detectors will simulate the airborne situation and the position of the aircraft on the pads will not be too critical.

In calculating how thick the pads should be, it is first necessary to calculate how the radiation from the pads varies with their thickness. From equation (2) the count rate (N) at an altitude h above an infinite source is given by

$$N = A\,E_2(\lambda h) \qquad (6)$$

where λ, A and E_2 have been defined previously. The constant A is the count rate at ground level when h is zero.

The radiation N_D detected from an infinite slab of thickness D is therefore given by

$$N_D = A(1-E_2(\mu D)) \qquad (7)$$

where μ is the linear attenuation of gamma radiation in the ground. The radiation detected from a source of thickness D, compared to the total radiation from an infinite source, expressed as a percentage P, is therefore given by

$$P = 100\,(1-E_2(\mu D)) \qquad (8)$$

Figure 6 and Table 5 show how this percentage (P) varies with D, the thickness of the pads, for thorium gamma radiation of energy 2.62 MeV. In using equation 8 it was assumed that the concrete of the pads had a density of 2.2 gm/cm^3 and a mass absorption coefficient of 0.0396 cm^2/g which corresponds to a linear attenuation coefficient (μ) of 0.087/cm.

The IAEA (1976) have recommended that the calibration pads should have a minimum thickness of 50 cm. Table 5 shows that this is a sufficient thickness for the pads to be effectively infinite and was therefore the value recommended for the Thailand pads.

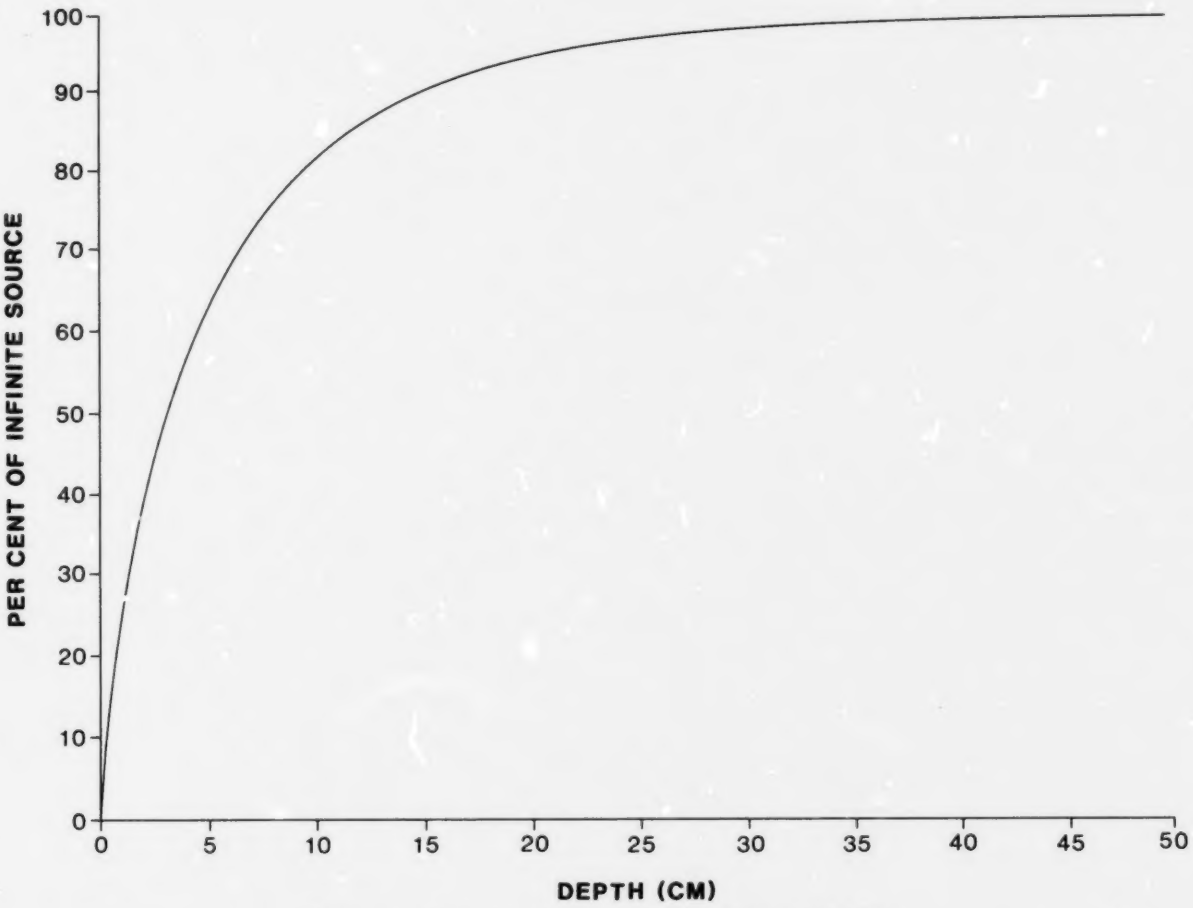

Figure 6. Response of infinite slabs of different thickness.

Table 5. Response of sources of different thickness (detector at ground level)

Source thickness (cm)	Percentage of infinite source
1.0	25.3
2.0	39.3
3.0	49.4
4.0	57.2
5.0	63.4
6.0	68.5
7.0	72.8
8.0	76.4
9.0	79.4
10.0	82.0
12.5	86.9
15.0	90.4
17.5	92.9
20.0	94.7
25.0	97.0
30.0	98.3
40.0	99.4
50.0	99.8

In using the pads for calibration, it is essential that while measuring the radiation from one particular pad, the radiation detected from any of the other pads should be negligible.

A pad of area, a, at a large horizontal distance, d, from the point of detection, will subtend a solid angle, θ, given by

$$\theta = \frac{ah}{(h^2+d^2)^{\frac{3}{2}}} \qquad (9)$$

If the height of the detector above the ground, h, is much smaller than d, this reduces to

$$\theta = \frac{ah}{d^3} \qquad (10)$$

The radiation on one pad will then be reduced at another pad by a factor f, given by

$$f = \frac{ah}{2\pi d^3} \qquad (11)$$

In theory the value of f will be somewhat lower than predicted by this simple practical formula due to the attentuation of gamma radiation in the air.

The IAEA recommended that circular pads 8 m in diameter should be 15 m apart, ie. 23 m from centre. Using equation (11), the radiation from one pad will be reduced by a factor of 0.0007 at an adjacent pad. Interference between

adjacent pads can therefore be neglected. For the Thailand pads, the IAEA recommendations were therefore followed, with the minimum spacing between the pads being 15.2 m (50 ft.).

Particle size

Available information on calibration pads constructed in various parts of the world shows that a major problem which limits their effective use relates to the difficulties of establishing reliable estimates of their concentrations. Table 6 shows the mean concentration and associated errors of uranium and thorium ground and airborne spectrometer calibration pads constructed in Finland (Multala, 1981), Canada (Killeen, 1979 and Grasty and Darnley, 1971), United States (Ward, 1978).

An initial examination of these results suggested that the calibration pads with large uncertainties in their concentrations are inhomogeneous because a small amount of high concentration material had not been well mixed with the concrete. However, a more detailed examination showed that the large spread in the results is due to problems in taking a representative sample of concrete containing a limited number of uranium particles.

The sampling problem was investigated for the portable spectrometer calibration facilities at Bell's Corners, Ottawa where the 7 per cent uranium ore used in the construction of the three uranium pads had a grain size between 6 and 40 mesh (0.4 to 3.4 mm). The grain size distribution of the particles was first determined. The average weight of particles within different mesh sizes was then determined by weighing 100 of these particles.

The analysis of the concrete samples taken during the pad construction was carried out on samples weighing approximately 400 g. The weight of the uranium in each concrete sample (W) is therefore given by

$$W = \frac{400}{70000} \times U \qquad (12)$$

where U (in ppm) is the final concentration of the concrete. This assumes the remaining constituents of the concrete have neglible uranium content.

From the grain size analysis, the average number of particles in a sample weighing 400 g could then be calculated for each mesh size. These results are presented in Table 7 for the calibration pad with nominal uranium concentration of 100 ppm which, from equation (12) will contain 0.58 g of 7 per cent uranium ore.

Because a random sample of concrete is taken, there will be a statistical spread in the number of particles of each mesh size in each sample. The standard deviation in the number of particles will be given by the square root of the average number of particles of each mesh size. This will contribute to a corresponding uncertainty in the weight of the uranium ore for that mesh size. The expected statistical spread in the total weight of uranium ore in each sample of concrete can then be calculated from the individual statistical errors. The results which are presented in Table 7

Table 6. Concentrations of some calibration pads

Location	Reference	Uranium Pad[1] (eU ppm)	Thorium Pad[1] (eTh ppm)
Canada	Killeen[2] (1978)	12.4 ± 12.1	10.3 ± 0.7
Canada	Killeen[2] (1978)	43.5 ± 16.2	79.8 ± 9.6
Canada	Killeen[2] (1978)	489.6 ± 100.9	381.5 ± 77.3
Canada	Grasty and Darnley (1971)	11.7 ± 0.8	40.8 ± 4.2
Finland	Multala (1981)	53.2 ± 7.4	104 ± 18
United States	Ward (1978)	30.3 ± 0.8	45.3 ± 0.4

[1] Uncertainties are at the 1 σ level
[2] The analyses for these facilities are more recent values than the preliminary results presented by Killeen (1978)

Table 7. Effect of particle size on the analysis of 400 g concrete samples of 100 ppm Uranium

Mesh Size	Percent of Particles	Average Wt. of Particles	Weight of Particles in 400 g Concrete Sample	Average Number of Particles	Average Wt. of Particles and 1 σ Error in 400 g Sample
-40	0.86	<0.0001 g	0.005 g	50 ± 7.1	0.005 ± 0.0007
-20 + 40	3.8	0.0001 g	0.022 g	220 ± 15	0.022 ± 0.0015
-12 + 20	31.3	0.0016 g	0.182 g	114 ± 11	0.182 ± 0.0171
-10 + 12	11.1	0.0078 g	0.064 g	8.2 ± 2.9	0.064 ± 0.0230
+10	53.0	0.0298 g	0.307 g	10.3 ± 3.2	0.307 ± 0.095
		Total Wt.	0.58 g	Total Wt. of Uranium Ore	0.58 ± 0.10

show that it is the few large particles which have the major contribution to the statistical spread in the total weight of uranium ore in each 400 g sample. A statistical spread of 0.10 g in the total weight of 0.58 g of uranium ore will result in an expected spread of 17 ppm in the analyses of a calibration pad with a nominal concentration of 100 ppm.

Based on the particle distribution of the uranium ore used in the Bell's Corners portable calibration facilities (Killeen, 1979), the calculated and measured spread in the analysis of the concrete samples were compared for the 10 ppm, 50 ppm and 500 ppm uranium pads. These results are presented in Table 8 and show that the statistical spread in the analyses can be largely explained by the limited number of particles present in each sample. Similar calculations showed that in the case of the Finland pads (Table 6) the relative large spread in the uranium and thorium analysis can also be explained by the large particle sizes of up to 25 mm which were used (Multala, 1981).

Table 8. A comparison of the experimental and theoretical errors in the analyses of concrete samples from the portable calibration facilities, Bell's Corners, Ottawa, Canada

Nominal Uranium Concentration	Measured Concentration and Associated Error	Assumed Concentration and Calculated Error
10 ppm	12.4 ± 12.1 ppm	10 ± 5.5
50 ppm	43.5 ± 16.2 ppm	50 ± 12
500 ppm	489.6 ± 100.9 ppm	500 ± 39

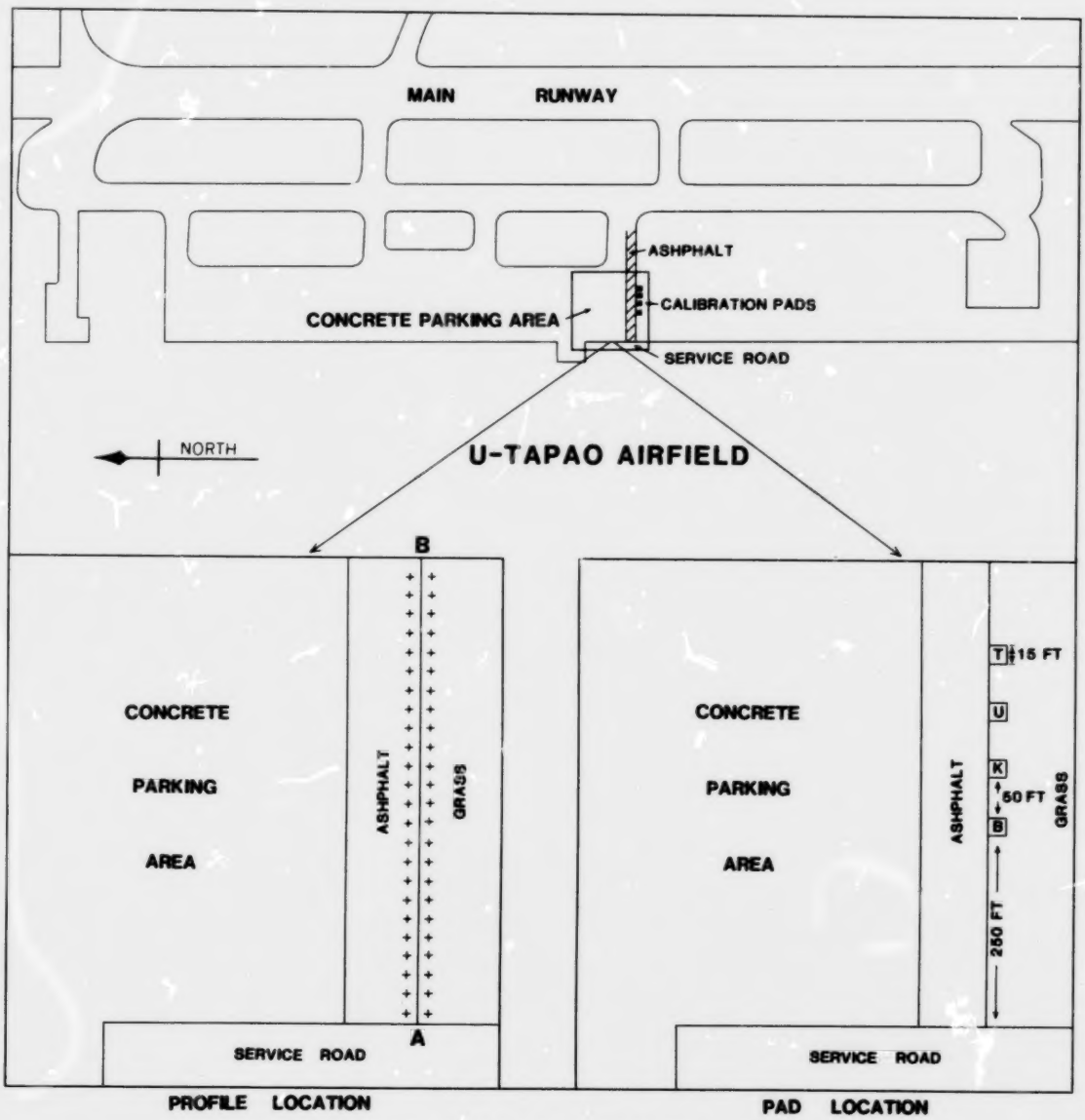

Figure 7. U-Tapao airfield showing ground profile and pad location.

In the case of the airborne calibration facilities at Uplands Airport, Ottawa (Grasty and Darnley, 1971), the spread in the analyses of cores taken from the concrete pads (Table 6) is considerably lower than for the Bell's Corners facilities. However the spread is still higher than expected considering that the thorium and uranium ore was powdered before it was mixed with the concrete.

Analysis of the aggregate used in the concrete showed it to consist of glacially derived gravel composed of a variety of Canadian Shield rock types. It would be expected that the uranium and thorium content of the different rock types would vary considerably. Consequently, the variation in the analysis of the cores was attributed to fluctuations in the proportions of the various aggregate material present in the concrete cores. Based on these studies an important consideration in obtaining new and reliable estimates of the pad concentrations is the particle size of the materials used. This particle size must be considered in conjunction with the quantity of material analyzed and its concentration.

PAD CONSTRUCTION

Site selection

In April 1984 a detailed investigation was carried out at U-Tapao Airport, approximately 120 km southeast of Bangkok, to locate a suitable site for the four calibration pads.

The main requirements were that the site should be:

1. readily accessible to aircraft,
2. sufficiently large to accommodate the four pads with their required separation,
3. topographically flat
4. uniform in radioactivity.

Due to the large size of the pads and their required separation, the initial search for a site was directed to areas of flat ground adjacent to an existing aircraft parking area which were at least 60 m (200 ft.) in length. Two possible sites meeting these requirements were identified and then surveyed with a portable scintillometer to locate areas which were radioactively homogeneous. Figure 7 shows the site which was found to be homogeneous and was subsequently selected by the airport authorities because it had the least interference with regular aircraft traffic. This particular site had the added advantage that it was close to a large warehouse which was used to store the construction material under cover, so that they could be kept dry. Figure 8 shows the results of the radioactivity measurements at this site which were taken with a Rank scintillometer at the locations indicated in Figure 7. A total of 26 measurements were carried out at 15 m (25-ft.) intervals both on the asphalt strip of the aircraft parking area and on the adjacent ground. The precise location for the calibration pads was chosen to avoid an area at the western edge of the parking area with somewhat variable levels of radioactivity apparently related to small topographic depressions.

In addition to the scintillometer measurements three spectrometer measurements were performed on the asphalt strip and the ground at the locations indicated. These measurements were carried out to check that the background levels of radioactivity of the material surrounding the pads would not contribute significantly to measurements on the pads. The asphalt and the adjacent ground were found to have similar values of approximately 1 per cent potassium and 3.5 to 4.0 ppm equivalent uranium. The thorium concentrations of the ground (approximately 10 ppm) was somewhat higher than the concentration of the asphalt which was approximately 6.0 ppm. In view of the recommended radioactivity levels for the pad concentrations and the relatively small contribution of the background to any measurement of the pads, no problems were anticipated due to the radioactivity levels in the vicinity of the pads.

Material selection

In order to avoid the sampling problems described previously it was decided to construct the Thailand pads following similar procedures and with similar materials used for the construction of the U.S.A. calibration pads at Walker Field, Grand Junction, Colorado. For the uranium and thorium pads a small amount of suitably crushed high activity uranium and thorium ores was added to masonry sand and cement in the ratio of 3 to 1. The potassium pad was manufactured essentially from potassium feldspar and cement also in the ratio 3 to 1. No coarse aggregate was used in any of the pads. The lack of aggregate was not anticipated to cause any problems in Thailand since the strength of the concrete (strictly mortar) was not considered to be a critical factor, as the pads were only required to support an aircraft. The small annual temperature fluctuations and the lack of frost further reduced the importance of using an aggregate.

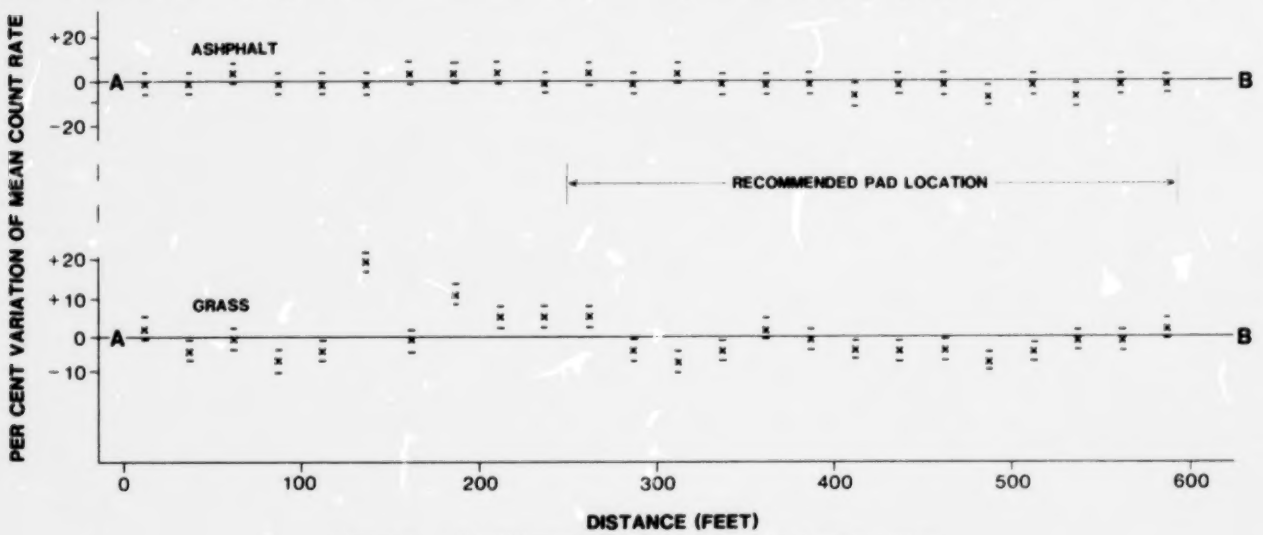

Figure 8. Scintillometer profile used to select pad location.

Table 9. Analysis of pad material

Material	Source	Use	K%	eU (ppm)	eTh (ppm)
Cement	Supplied by Kenting	All Pads	0.5	2.0	4.5
Silica Sand[1]	Near Rayong	Blending with U & Th ores	0	0.4	1.0
Masonry Sand	Near Rayong	Pad Matrix	0	0.5	2.5
K-Feldspar	Ratburi	K Pad	8.1	0.03	0.3
Uranium ore[2] (Faye et al, 1979)	Canada	U Pad	0.4	70,900	40
Monazite	BSMC Mining Co. - Rayong	T Pad	?	2,800	70,000

[1] This material was originally proposed for the pad matrix.
[2] Subsequent analysis of the crushed and blended uranium ore gave a uranium concentration of 56 500 ppm.

Table 10. Mineral composition of construction materials

Silica Sand	Quartz	99.8%
	Hornblende	0.2%
	Zircon	< 0.1%
Masonry Sand	Quartz	88.4%
	Feldspar	11.5%
	Magnetite, Hornblende, Zircon Garnet, Monazite	0.1%
K-Feldspar	Feldspar	93.6%
	Quartz	5.3%
	Muscovite	1.0%
	Muscovite, Biotite, Garnet Apatite, Magnetite, Hornblende	0.1%
Monazite Sand	Monazite	97.7%
	Hornblende	1.3%
	Zircon	0.6%
	Magnetite	0.4%
Uranium Ore (Faye et al, 1979)	In decreasing order of abundance: plagioclase, feldspar, quartz, uraninite, calcite and dolomite, hematite, chlorite and muscovite, galena, carbon. Percentage of weight of remaining minerals is approximately 2%.	

Apart from uranium, all the materials for the pads are readily available in Thailand. For the potassium pad, potassium feldspar which is used in the ceramic industry was obtained from a mine at Ratburi. Suitable thorium in the form of monazite for the thorium pad was located at a small tin mining operation, close to U-Tapao, where the monazite was separated from the beach sand and conveniently packaged in 50 kg bags. Low radioactivity masonry sand for the pad matrix was located near Rayong, also near U-Tapao. Extremely low radioactivity pure silica sand which is used in the manufacture of glass was found near the source of the masonry sand and was used to dilute the high activity thorium and uranium ores in a two stage blending procedure. This particular silica sand was too fine for use as the pad matrix but was ideal for blending with the monazite and crushed uranium ore because of its similar grain size.

Because of the difficulty of obtaining high grade uranium ore in Thailand, the GSC agreed to provide the uranium ore. The most important aspect in the selection of a suitable uranium ore relates to the emanation of radon. Any loss of radon from the uranium ore material will reduce the gamma-ray activity of the uranium ore since radon precedes the gamma-ray emitter bismuth-214 in the uranium decay chain.

In 1978, Løvborg et al reported significant seasonal changes in the gamma-ray activity of the uranium pad which had been constructed in 1971 at Risø in Denmark. These changes were attributed to a partial loss of radon from the pad. It was generally found that the gamma-ray activity was highest in winter because the concrete pore spaces were filled with water or ice thereby retarding the migration of radon to the pad surface. Similar seasonal changes had been observed in the gamma-ray activity of the uranium pad at Walker Field, Colorado (Stromswald, 1978).

The Canadian uranium ore material selected for the Thailand pads came from Beaverlodge, Saskatchewan and had been used in the construction of the portable calibration facilities and model boreholes at Bell's Corners, Ottawa (Killeen, 1979). This particular pitchblende ore has been extensively studied and has been shown to lose less than 2% of its radon in a dry state (Grasty and Dyck, 1984). Besides being a low emanator of radon, it has the added advantage that it appears to be in radioactive equilibrium and unlike many other uranium ores had negligible thorium (Faye et al., 1979). Because of these characteristics, this ore has been selected by the International Atomic Energy Agency as an International uranium standard for calibrating laboratory gamma-ray spectrometers.

Samples of the monazite sand, potassium feldspar, masonry and silica sand were shipped to Ottawa and analyzed by gamma-ray spectrometry following the procedures described by Grasty et al. (1982). A sample of cement which was to be used in the construction was also analyzed to ensure that it did not have unusually high radioactivity. In some cases cement may contain as much as 10 ppm of uranium or thorium (Løvborg, 1984). The thorium and

uranium ores were first diluted with the fine silica sand to approximately 1000 and 500 ppm respectively because of their high activity which would overload the laboratory gamma-ray spectrometer.

The results of the analysis of these materials are shown in Table 9 and were used to calculate the quantities of sand, cement and radioactive materials required. The mineral composition of the materials used in the pad construction is shown in Table 10. The minerals were first separated by a combination of heavy liquids and magnetic methods and subsequently identified by X-ray diffraction.

Material requirements

The quantity of material required for each pad was calculated assuming concrete (mortar) manufactured with sand and cement in the ratio of 3 to 1 would have a density of 2 gm/cc. This density was typical for the U.S.D.O.E. calibration pads which were manufactured with the same sand to cement ratio. Approximately 10 per cent of additional material was acquired as a precautionary measure to allow for minor modifications during the construction process.

Table 11 shows the quantity of material which was acquired for each pad. The weights were calculated in kilograms of dry material assuming that for every kilogram of cement in the concrete there will be 0.25 kg of chemically bound water. Each pad has a volume of 26.55 m^3 which with a density of 2 gm/cc would have a total weight of 53.1 metric tons. With the safety margin of 10 per cent, this becomes 58.4 metric tons for each pad. The weights of the masonry sand, cement and potassium feldspar were calculated to the nearest 100 kg which proved to be convenient during construction since these materials were bagged in 50 kg quantities.

By manufacturing the pads using all the materials shown in Table 11, the uranium pad will have a final uranium concentration of 22.6 ppm and the thorium pad a thorium concentration of 45.8 ppm. These concentrations are somewhat higher than the recommended values shown in Table 2 to allow for sampling and possible losses during the blending and homogenising procedures. In the case of the potassium pad, the maximum potassium concentration that can be achieved is obtained by using only potassium feldspar and cement. This will result in a final concentration of 5.8 per cent, somewhat lower than the recommended value of 8 per cent.

Preparation of materials

Following the field investigation of the possible sites for the calibration pads and the selection of the materials, a report was prepared on the construction of the pads. This report was submitted to DMR, Thailand and to Kenting for their subcontractor PAE (Thailand) Co. Ltd. selected for the construction. The information in this report on the preparation of the materials closely follows the procedures for the construction of the U.S.D.O.E. calibration pads (Ward, 1978).

The successful construction of the U.S.D.O.E. calibration pads, as measured by their degree of homogeneity was felt to be attributed to three important factors. These were 1) the blending of all the materials in the dry state, 2) the grain size of the materials and 3) the two stage blending procedures for diluting the uranium and thorium ores.

In the construction of the U.S.A. pads, all the pre-blended materials were stored in metal drums which were then poured into cement trucks during construction. This required labelling and storing in excess of 1000 drums and was felt to be an unnecessary logistical and practical problem. For the Thailand pads, all the materials were blended dry on site in a cement truck, after which water was added and the pads poured immediately.

For logistical reasons, the materials for each pad were divided into six 'lots'. Since each pad has a volume of 26.5 m^3, the amount of material in each cement truckload will be approximately 4.9 m^3, including the additional safety margin of 10 per cent. This volume of material could be well mixed in the six cubic-metre cement trucks used in the construction. It turned out that the masonry sand, cement and potassium feldspar all came in convenient 50 kg bags. It was therefore unnecessary to label and store the materials for each cement truckload separately provided the required number of bags were assigned to each truck during construction. In the case of the uranium and thorium ore, these were stored in labelled containers.

Table 11. Materials acquired

	B-Pad	K-Pad	U-Pad	T-Pad
Masonry Sand (Kg)	41,400		41,400	41,400
Cement (Kg)	13,800	13,800	13,800	13,800
K-Feldspar (Kg)	-	41,400	-	-
U-Ore (Kg)	-	-	18	-
T-Ore (Kg)	-	-	-	36
Water Content (Kg)	3,450	3,450	3,450	3,450
Total Weight	58,650	58,650	58,668	58,686

Table 12. Grain size analysis of construction material

		Percentage within this grain size			
Mesh Size	Particle Size (mm)	Masonry Sand	K-Feldspar	Monazite Sand	Uranium Ore
+12	+1.41	25.1	-	-	-
-12+60	-1.41+0.25	74.7	70.3	-	-
-60+100	-0.25+0.15	0.1	8.6	37.5	-
-100+200	-0.15+0.074	0.1	7.6	59.4	100
-200	-0.074	0.1	12.8	2.4	-

To avoid any of the sampling problems discussed previously, careful consideration was given to the grain size of the uranium and thorium ores.

A grain size analysis of the monazite sand for the thorium pad was carried out and showed that almost all the material had a grain size less than 0.25 mm (Table 12). Approximately three hundred grains were weighed and found to have an average weight of 14×10^{-6} g. Using equation (12) it was calculated that there were approximately 10 000 individual particles in a 400 g concrete sample with a thorium concentration of 40 ppm. Assuming all the particles had the same weight, this would result in a statistical error of only 1 per cent in the analysis of 400 g concrete samples from the thorium pad. Further crushing of the monazite sand was therefore considered to be unnecessary.

The uranium ore from Beaverlodge, Saskatchewan had been crushed to a grain size between 0.4 and 3.4 mm. This grain size had been shown to contribute significantly to uncertainties in the analysis of concrete samples from the Bell's Corners pads. Rough calculations, assuming the grains were spherical and had a density of 4 g/cm^3 indicated the uranium ore should be crushed to -0.15 mm to avoid significant errors due to sampling. This was consistent with the conclusions for the monazite sand. However, crushing a rock increases the surface area with the possibility that there will be an increase in the emanation of radon (Tanner, 1980). As pointed out by Løvborg (1984), there is therefore a conflict in choosing the particle size into which the ores should be crushed. In the case of the uranium ore selected, it has been shown by Grasty and Dyck (1984) that when ground to -0.074 mm (-200 mesh) the dry ore emanates less than 4% of the radon produced. The uranium ore was therefore crushed to -0.15 mm (-100 mesh) and to avoid any possible problems due to radon emanation, the -0.074 mm (-200 mesh) fraction was discarded. The remaining material was then blended for approximately two hours.

Figure 9. A drum of U-500 uranium concentrate prepared by mixing uranium ore with fine silica sand.

Figure 10. Drums of U-500 concentrate with the drum used to ship the Canadian uranium ore to Thailand.

Because of the extremely small amount of uranium ore required for the uranium pad a two stage blending procedure was carried out with the uranium ore. The first stage was designed to produce a 500 ppm uranium concentrate which was called U-500, by blending the nominal 7 per cent uranium ore with the low radioactivity silica sand (Fig. 9). With its similar grain size (Table 12), it was anticipated that any separation of the two materials during the blending process would be minimized.

The concentration of 500 ppm was chosen since it was sufficiently radioactive to be measured quickly and reliably in the GSC laboratory gamma-ray spectrometer without causing any spectral distortion due to the large-volume sodium iodide detector system (Grasty et al., 1982).

A similar two stage blending procedure was carried out with the monazite for the thorium pad. In this case, the thorium ore was diluted to 1000 ppm which gives it a similar gamma-ray activity per gram as the 500 ppm uranium concentrate.

The crushed uranium ore was sent by air freight to Thailand in eight 3-kg packages (Fig. 10). Three kilograms were required for each of the six lots, corresponding to the six cement truck loads.

For each of the six 'lots', the following blending procedure was specified in the construction report submitted to DMR, Kenting and their sub-contractor:

> 'Take one 3 kg package of the uranium ore and blend it with 423 kg of dry silica sand to produce a homogeneous 500 ppm uranium concentrate (U-500). A two hour blending time is recommended, with the ore being added a little at a time to help the mixing process. We also recommended that the mixer only be half full to speed the blending. Depending on the blending facilities, the material for each lot can be blended in smaller quantities. To check the homogeneity of the U-500 concentrate, 3 random samples of 500 gm each, labelled with the lot number are required. If any lot proves to be inhomogeneous, it will have to be subjected to further blending and rechecking. After sampling, the blended material should be stored in drums labelled U-500, with a lot number (1 to 6) and a drum number for that lot.'

A similar blending procedure was specified for producing the 1000 ppm thorium concentrate, called T-1000. In this case 6 kg of the 7.0% thorium ore was to be mixed with 414 kg of silica sand. Three random 500 gm samples from each 'lot' were also taken for analysis.

After the materials were blended, the 36 samples of the U-500 and T-1000 uranium and thorium concentrates were air freighted from Thailand to Ottawa for analysis. The samples were packed into laboratory sample cans and immediately analyzed using a two-minute counting time which was found to be sufficient for counting erros to be negligible. The results of these analyses are shown in Table 13.

Based on the lack of homogeneity of both the thorium and uranium concentrates, the contractor was instructed to repeat the blending process. In this second operation the material for each lot was first well mixed by hand, before being blending in the mixer for a further two hours. The results of the analysis after this second further blending are shown in Table 13. Although the analyses still show some degree of inhomogeneity, they are a significant improvement on the first blending. The second blending was considered to be adequate, since almost all the U-500 and T-1000 were to be used in the pads, and would therefore receive additional mixing in the cement trucks. The reason for the blending problem was attributed to using a mixer which was completely full, and therefore did not allow the materials to mix when the drum was rotated. This problem was further compounded because the ores were added to the mixer after the entire quantity of silica sand had been loaded into the mixer (Fig. 11).

The results of the U-500 analyses show that there is a considerable discrepancy from the intended value of 500 ppm. This was only of minor concern since there was considerably more U-500 prepared than was originally to be used. In addition, by reducing the amount of sand and cement, which had a 10 per cent safety margin, the concentration of the uranium pad could be further increased. Subsequent analysis of the uranium ore showed that it had a concentration of 5.65% which almost exactly accounted for the discrepancy between the measured and calculated values for the U-500. The uranium ore had been assigned the recommended value of 7.09% for the CANMET uranium standard BL-5 (Faye et al., 1979). However, the uranium ore for BL-5 and the Thailand pads was part of a large quantity of ore (approximately 5000 lbs.) that had originally been hand-picked before being purchased by the GSC. Apparently, the hand-picked samples of the ore had variable uranium concentrations. Part of the difference could also be attributed to the selection of a particular grain size which could also affect the concentration.

Figure 11. The full drum of silica sand which initially resulted in an inhomogeneous U-500 uranium concentrate.

Table 13. Analyses of U-500 and T-1000 concentrates

	U-500 (ppm)			T-1000 (ppm)		
	Mean		Range	Mean		Range
After first blending	440	± 237	44-838	1377	± 655	78-2409
After second blending	408	± 22	384-464	1048	± 62	925-1132

The results of the T-1000 analyses also show a small but significant difference from the calculated values of 1000 ppm. This was believed to be due to the use of a different bag of monazite from the one analyzed by the GSC. Analysis by the Atomic Energy for Peace in Thailand had shown that the monazite which was used to prepare the T-1000 had a thorium concentration of 7.25%. The difference between this value and 7.0% almost exactly accounts for the observed difference between the measured and calculated values for the T-1000, thorium concentrate.

Because no dilution is required for the potassium feldspar for the potassium pad, the feldspar was simply crushed to sand size by making sure that the material passed through a 10 mesh sieve. The required amount of material was then packed in 50 kg bags.

Construction procedures

Following the submission to DMR of the GSC report on the method of construction of the pads and the field investigation of the possible sites, the one selected was prepared for construction.

The site for each pad was excavated to a depth of 70 cm (24 in.) and a 15-cm (6 in.) slab of standard construction concrete poured at the bottom. This slab was to support the pads which with no coarse aggregate are therefore susceptible to cracking if there is any movement of the underlying soil. The slabs extended a distance of 30 cm (12 in.) beyond the edges of the pads. Removable wooden forms, approximately 50 cm (20 in.) high and extending 5 cm (2 in.) above the level of the adjacent aircraft parking area, were then constructed on each slab. The planned 45-cm (18-in.) height of each pad was marked on the sides of the forms.

A polyethylene sheet was laid on top of the concrete slabs to reduce any possible radon loss from the pads or the migration of radon through the ground and into the pad itself. The sides of the pads were also to be sealed with tar.

The construction of the four pads was carried out on 6, 7 July 1984. The blank pad and the potassium pads were constructed on the first day and the uranium and thorium pads on the second day. The blank and potassium pads were constructed first since for these pads mixing and homogenizing is not critical. The experience gained in their construction proved to be useful for developing a smooth operation for the more complicated uranium and thorium pads where the addition of the uranium and thorium concentrates is required. It is fortuitous that the first truckload, where practical problems are more likely to arise, ends up at the bottom of the pad and therefore has the least influence on a gamma-ray

measurement at the pad surface. Correspondingly, by the time the top layer is poured any problems in the construction methods are likely to be resolved.

The dry sand, cement and feldspar were stored in 50-kg bags in a large warehouse approximately 200 m from the construction site (Fig. 12). Based on the amounts of materials shown in Table 11 for the blank pad, each of the six cement trucks require 2300 kg of cement and 6900 kg of sand. This corresponds to 46 bags of cement and 138 bags of sand. The trucks were loaded by hand from a metal step ladder on the warehouse loading dock (Fig. 13). Two trucks were loaded at a time, with one bag of cement followed by three bags of sand. The loading operation for the two trucks generally took between 30 and 40 minutes. The weights of the sand and cement were initially checked while the first two trucks were being loaded and found to average 50.3 and 50.4 kg respectively. The weights of the bags of sand showed some minor variations but this was not considered to be important because of the large number of bags required for each truck.

After the addition of water, the wet concrete was mixed for 15 to 30 minutes and then poured into the wooden forms. Each truckload was spread across the area of the pad by hand so that any differences in the composition of the concrete from each truck would to some extent be averaged out for a gamma-ray measurement made at the pad surface (Fig. 14, 15).

Figure 12. The warehouse with the bags of sand, cement and feldspar.

Figure 13. Loading a bag of sand into a cement truck.

Figure 14. The pouring of the pads showing the wooden forms.

Figure 15. Spreading the sand-cement mix across the pad.

As a precautionary measure, ten per cent of additional material had been allotted for each pad. Coincidentally the wooden forms were constructed to a height of 45 cm (20 in.) which exceeds the planned depth of the pad also by 10 per cent. Since an additional depth of 5 cm (2 in.) was not anticipated to cause any problem in using the pad, no adjustments were made to the quantity of material added to the last truck and all the materials indicated in Table 11 were used for the blank pad.

In the preparation of the wet concrete mix, it had been intended to add only enough water to produce a two-inch slump. The purpose of the low slump was to avoid any possible settling of the dense uranium and thorium particles and to give strength to the concrete by minimizing the amount of water. However, in practice there was no accurate method of controlling the amount of water and the resulting mixture depended largely on the experience of the truck operator. Initial attempts at producing a low slump mixture were soon abandoned for a more workable mixture because of the difficulty of spreading a low slump concrete across the large area of the pads. Subsequent analysis of concrete samples taken during the construction showed that no significant problems arose due to the lack of control of the water content.

The potassium feldspar pad was constructed following the same procedure used for the blank pad. However, considerably more water was required for the potassium pad because the potassium feldspar had been crushed to -1.7 mm (-10 mesh) which resulted in a large fraction of fine material (see Table 12). In retrospect, more control should have been

taken in the crushing of the feldspar to achieve a suitable range of particles sizes for a strong concrete. Alternatively, at an earlier stage it would have been advantageous to strain off the very fine particles (less than 0.074 mm (200 mesh)). In spite of the large proportion of fine particles, no problems have been encountered in the use of the potassium pad.

The U-500 concentrate had a uranium concentration of approximately 400 ppm (Table 13) which is considerably lower than the intended value of 500 ppm. Consequently the planned construction procedures for the uranium pad were modified to some extent, in an attempt to reach the recommended value of 20 ppm (Table 2). This could best be achieved by mixing the entire U-500 concentrate with the minimum quantity of sand and cement which was sufficient for a 40 cm (18 in.) thick pad. For each truck it was calculated that 123 bags of sand mixed with 44 bags of cement and the entire 423 kg of U-500 concentrate would give the required 3 to 1 sand to cement ratio (3 kg of the prepared 426 kg of U-500 had been shipped to Ottawa for analysis).

In order that the sand, cement and uranium concentrate were properly mixed, the materials were added in approximately the correct proportions while the drum of the cement truck was rotating. Three bags of sand were followed by one bag of cement and approximately 10 kg of uranium concentrate. The 10 kg of concentrate was estimated by volume using a plastic bucket marked at the appropriate level (Fig. 16, 17). With this method, no weighing was required and the loading of the trucks was speeded up considerably. An exact weight of 10 kg is not important since all the concentrate was added. After 123 bags of sand, 41 bags of cement and approximately 410 kg of concentrate were added to each truck, the remaining three bags of sand and approximately 13 kg of concentrate were loaded. Each loaded truck was blended dry for 15 minutes. Water was then added and the wet mix blended for a further 15 to 30 minutes before the concrete was poured. The final thickness of the uranium pad was 48 cm (19 in.).

The T-1000 concentrate had a thorium concentration close to the planned value of 1000 ppm (Table 13). Since an additional ten per cent of concentrate had been prepared, it was necessary to remove some of this material from each of the six lots. Based on the analysis of the T-1000 concentrate and the thorium concentration of the sand and cement (Table 9), it was calculated that 372 kg of concentrate were to be mixed in each truck with 46 bags of cement and 130.5 bags of sand. The procedure for adding the materials was similar to that used for the uranium pad. In the case of thorium pad three bags of sand were followed by one bag of cement and 8.5 kg of concentrate. After the addition of 129 bags of sand, 43 bags of cement and approximately 365.5 kg of concentrate, the remaining 1.5 bags of sand, 3 bags of cement and 6.5 kg of concentrate were added.

Figure 16. Measuring the U-500 uranium concentrate into plastic buckets.

Figure 17. Loading the U-500 uranium concentrate into a cement truck.

Because of a delay in the arrival of some missing bags of sand, the amounts of material for the last truck were reduced by a factor of two. The thorium pad was therefore reduced in depth compared to the blank and potassium pad to a measured value of 45 cm (18.1 in.). Table 14 shows the amounts of material that were used in the pad construction which are based on the measured weights of 50.3 kg, 50.4 kg and 50.0 kg for the nominal 50 kg bags of sand, cement and feldspar. The final depth of each pad is also shown.

On the day following the construction, a series of portable spectrometer measurements were taken on the newly formed concrete pads to check their homogeneity (Fig. 18). A total of 49 one-minute measurements were carried out on a 7 by 7 grid with the measurement points approximately 1 m apart. The number of counts recorded in the radioelement window on the potassium, uranium and thorium pads are shown in Table 15 together with the statistical spread of the individual 49 measurements. A comparison of the theoretical spread (also shown) with the experimental values shows no detectable inhomogeneities in these pads. The total count window also established that any inhomogeneities were small and less than four per cent. However, these results are not shown because of minor spectral drift which occurred while the measurements were being taken.

After the pads had cured, the wooden forms were removed and the sides of the pads sealed with tar to reduce any migration of radon into or out of the pads. The area

Table 14. Total materials used in pad construction

	B-Pad	K-Pad	U-Pad	T-Pad
Masonry Sand (Kg)	41650	-	37120	36100
Silica Sand (Kg)	-	-	2520	2020
Cement (Kg)	13830	13830	13300	12750
K-Feldspar (Kg)	-	41400	-	-
U-Ore (Kg)	-	-	17.9	-
T-Ore (Kg)	-	-	-	29.2
Depth of Pad in cm (in.)	50.8 (20.0)	50.8 (20.0)	48.5 (19.1)	46.0 (18.1)

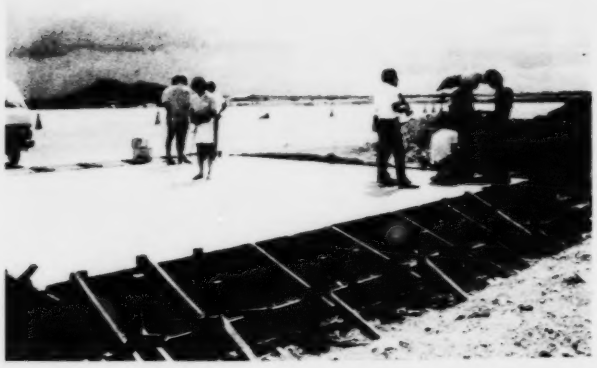

Figure 18. Checking the homogeneity of the pads with a portable gamma-ray spectrometer.

between the pad and the ashphalt aircraft parking area, which was approximately 20 cm wide was then filled with standard construction concrete so that an aircraft could easily taxi onto the pad. The concrete also prevented the edges of the somewhat brittle concrete of the pads from fracturing. The remaining excavated area, approximately 1 m wide, around the other three sides of the pads was then filled with material removed during the excavation.

PAD CONCENTRATIONS

In order that the pads can be used for the accurate calibration of gamma-ray spectrometers, it is essential that the radioactive concentrations of the pads be well known. Samples of the wet concrete mix were therefore taken during the construction. The uranium and thorium pads were constructed with a small amount of concentrate which is mixed with a large quantity of relatively inert sand and cement. On the other hand the potassium and blank pad were manufactured from materials which have a much smaller variation in radioactivity and weight. Consequently, if the materials for the pads are not well mixed the analyses of samples from the uranium and thorium pad would be expected to show much more variation than samples from the blank and potassium pad. However, a gamma-ray spectrometer is sampling a large volume of material and it is therefore the accuracy of the mean concentrations of all samples that governs the accuracy of the calibration. By increasing the number of samples analyzed, the mean value is known more accurately. More samples were therefore taken from the uranium and thorium pad because these pads were expected to show more variation than samples from the blank and potassium pad.

Table 15. Portable gamma-ray spectrometer homogeneity tests on the Pads

	Average Window Counts in 1 minute	Measured Variation (1 σ)	Theoretical Variation (1 σ)
K-Window (K-Pad)	184.0	16.6	13.6
U-Window (U-Pad)	56.2	7.4	7.5
T-Window (T-Pad)	60.1	7.3	7.8

As the concrete was being poured, samples were collected directly into weighed and labelled metal laboratory gamma-ray spectrometer sample cans (Fig. 19). The weight of the concrete in these cans were typically 400-500 g. Six samples were taken from each truckload used to construct the blank and potassium pad making a total of 36 samples from each pad. It was planned to take 12 samples from each truck for the uranium and thorium pad. Because the last truck for the thorium pad had only one-half the volume of material, only six samples were taken from this truck. Consequently a total of 72 samples were taken from the uranium pad and 66 samples from the thorium pad. It was anticipated that with this number of samples, any differences in the composition of the concrete from the different trucks could be detected and allowances made in calculating the average composition of the pad, as viewed by a gamma-ray spectrometer at the surface of the pad. Also with 72 samples the statistical error on the mean value is reduced by $(72)^{\frac{1}{2}}$ compared to the spread of the individual analyses. Consequently, relatively large statistical errors in the sample analyses can be tolerated. No evidence was found for a difference in the composition of any of the six truckloads required for each pad.

In addition to the samples taken for radioelement analysis, two concrete samples were taken from each truck for the measurement of density and porosity (Fig. 20). The 48 samples, which each weighed approximately 350 g, were collected in small labelled plastic containers. Since the pads are effectively infinite in depth, density has no effect on the calibration results. However, for those constructing similar facilities, density is a useful parameter to know. Porosity provides information on the magnitude of possible changes in the radioelement concentration of the pads that can arise from fluctuations in their moisture content. Such changes have been observed in the United States (Stromswald, 1978). Table 16 shows the density and porosity of the 12 concrete samples taken from each pad during construction.

Figure 19. Sampling the sand-cement mix as it was being poured.

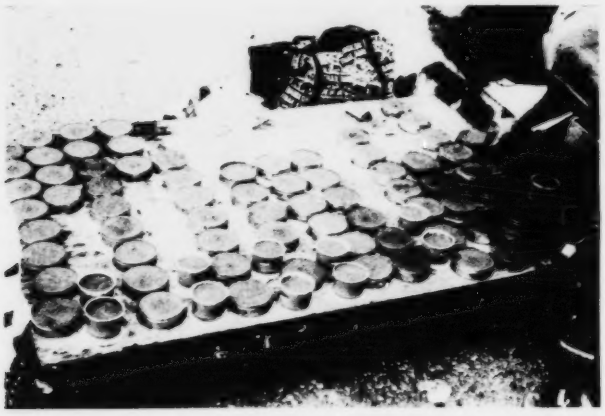

Figure 20. Metal sample cans for gamma-ray analyses and plastic containers for density and porosity.

The question of the moisture content of the concrete samples when the analyses are carried out is one of the most difficult to resolve satisfactorily. Samples from the Grand Junction pads in the United States were crushed and dried at a temperature of 110°C before analysis (Ward, 1978). Similar methods of analyzing the concrete in pads has also been employed in Israel and South Africa (Løvborg, 1984). However, these analyses are clearly not representative of the conditions of the pad when a spectrometer is calibrated. The best compromise was considered to be to leave the concrete to dry naturally and then carry out the analyses. After the samples were collected, the cans were left open from 24 to 48 hours so that most of the free moisture would evaporate through the heat generated by the reaction in the concrete. The cans were then sealed and subsequently shipped to Ottawa for analysis.

The 210 concrete samples were left sealed for approximately one month and then analyzed by laboratory gamma-ray spectrometry, following the procedures described by Grasty et al. (1982). Calibration of the spectrometer was performed using three standards prepared from aged thorium nitrate which is now in radioactive equilibrium, potassium carbonate and a radium salt. The results of these analyses are shown in Table 17 together with the number of samples analyzed from each pad. The errors indicated are the one

Table 16. Density and porosity of the Thailand pads

	Wet Density (gm/cm^3)	Porosity (%)	Number of Samples
Blank	2.21 ± 0.02	14.3 ± 2.8	12
K Pad	2.10 ± 0.02	24.2 ± 2.1	12
U Pad	2.24 ± 0.02	17.2 ± 1.9	12
T Pad	2.22 ± 0.04	18.4 ± 2.6	12

Errors indicated are at the one sigma level.

$$\text{Porosity} = \frac{\text{Volume of free water in saturated sample}}{\text{Volume of sample}} \times 100$$

sigma spread of the individual analyses and do not take into account any uncertainties resulting from the calibration of the spectrometer. The results show the expected somewhat higher spread in the uranium and thorium pad analyses than for potassium.

By routinely monitoring the counts recorded from the three standards, errors in the potassium and thorium calibration were estimated to be 1 per cent while the uranium (radium) calibration had a value of 1.5 per cent. The error in the mean value of N samples with a total one sigma spread of σ is given by $\sigma/N^{\frac{1}{2}}$.

The combined error, E, in the mean concentration of a particular pad was then calculated using the formula

$$E^2 = \frac{\sigma^2}{N} + \left(\frac{CxP}{100}\right)^2 \qquad (13)$$

where P is the calibration error in per cent and C is the mean concentration of all N samples.

Apart from a minor amount of silica sand used in the blending of the uranium and thorium ores, the uranium and thorium pads have the same matrix as the blank pad. Consequently, the potassium concentration of the uranium and thorium pad should be the same as the blank pad. However, the results in Table 15 show that the potassium concentration of the uranium pad has a somewhat higher value than the blank. This is believed to be the result of the difficulty of correcting for the relatively large contribution of uranium gamma-rays in the potassium window. We have therefore assumed that the blank pad analyses are the best estimates of the concentration of all three pads. Similarly we have also assumed that the thorium analyses of the blank pad gives the best estimate of the thorium concentration of the uranium pad, which has no added thorium. In Table 18, the concentrations assigned to the pads are shown.

CALIBRATION – THEORY

In calibrating a gamma-ray spectrometer, it is necessary to derive the system stripping ratios. These stripping ratios are the ratios of the counts detected in one window to those in another window from a pure source of potassium, uranium and thorium and have been defined previously.

From measurements on a calibration pad, the potassium, uranium and thorium window count rates N_K, N_U and N_T are linearly related to its potassium, uranium and thorium concentrations C_K, C_U and C_T. The equations are:

$$N_K = S_{KK}\,C_K + S_{KU}\,C_U + S_{KT}\,C_T + B_K \qquad (14)$$

$$N_U = S_{UK}\,C_K + S_{UU}\,C_U + S_{UT}\,C_T + B_U \qquad (15)$$

$$N_T = S_{TK}\,C_K + S_{TU}\,C_U + S_{TT}\,C_T + B_T \qquad (16)$$

Table 17. Analysis of Thailand concrete samples

	K (pct)	eU (ppm)	eTh (ppm)	N
Blank	0.25 ± 0.02	0.91 ± 0.16	2.86 ± 0.26	36
K Pad	6.18 ± 0.10	1.46 ± 0.24	1.16 ± 0.34	36
U Pad	0.33 ± 0.04	16.21 ± 1.01	2.80 ± 0.41	72
T Pad	0.22 ± 0.04	2.54 ± 0.28	37.31 ± 1.64	66

N = Number of samples analyzed.
Errors indicated are at the one sigma level.

B_K, B_U and B_T are the background count rates arising from the radioactivity of the ground surrounding the pad, the radioactivity of the aircraft and its equipment plus the contribution from cosmic radiation and the radioactivity of the air. The S_{IJ}'s are nine constants to be determined and give the count rate in window I per unit concentration of element J. The six stripping ratios α, β, γ, a, b, and g are related to the various S_{IJ}'s by the equations:

$$\alpha = S_{UT}/S_{TT} \quad (17)$$

$$\beta = S_{KT}/S_{TT} \quad (18)$$

$$\gamma = S_{KU}/S_{UU} \quad (19)$$

$$a = S_{TU}/S_{UU} \quad (20)$$

$$b = S_{TK}/S_{KK} \quad (21)$$

$$g = S_{UK}/S_{KK} \quad (22)$$

Each of the equations (14), (15) and (16) have four unknowns, (the window sensitivities for potassium, uranium and thorium plus the background) and consequently from measurements on all four calibration pads the unknowns can be uniquely determined.

In practice the four sets of equations corresponding to each of the equations (14), (15) and (16) can be reduced to a set of three equations with three unknowns by subtracting the count rates and concentrations of the blank pad from those of the potassium, uranium and thorium pad. With this method the unknown backgrounds, B_K, B_U and B_T are removed from the computation. The 3 x 3 count rate matrix **N** is then related to the 3 x 3 concentration matrix **C** and the unknown 3 x 3 sensitivity matrix **S** by the matrix equation:

$$\begin{bmatrix} N_{KK} & N_{KU} & N_{KT} \\ N_{UK} & N_{UU} & N_{UT} \\ N_{TK} & N_{TU} & N_{TT} \end{bmatrix} = \begin{bmatrix} S_{KK} & S_{KU} & S_{KT} \\ S_{UK} & S_{UU} & S_{UT} \\ S_{TK} & S_{TU} & S_{TT} \end{bmatrix} \times \begin{bmatrix} C_{KK} & C_{KU} & C_{KT} \\ C_{UK} & C_{UU} & C_{UT} \\ C_{TK} & C_{TU} & C_{TT} \end{bmatrix} \quad (23)$$

where N_{IJ} is the count rate in window I on pad J minus the count rate in window I on the blank pad. Similarly C_{IJ} is the concentration of element I on pad J minus the concentration of element I of the blank pad. In matrix notation

$$\mathbf{N} = \mathbf{SC} \quad (24)$$

from which the sensitivity matrix containing the nine S_{IJ}'s in equations (14), (15) and (16) may be evaluated using

$$\mathbf{S} = \mathbf{NC}^{-1} \quad (25)$$

CALIBRATION – PRACTICE

Sealing of pads

On 5, 6, December 1984 a series of experiments were carried out at the U-Tapao calibration facility to investigate any possible radon loss from the uranium pad. The experiments consisted of measuring the count rate on the uranium pad with a GR-410 portable gamma-ray spectrometer and then covering the pad overnight with plastic sheet (Fig. 21). The measurements were then repeated and a further set of observations made three hours after the plastic sheet had been removed.

The initial interpretation of the results shown in Table 19 indicated that the plastic sheet had restricted the migration of radon gas out of the uranium pad allowing its gamma-ray activity to build-up overnight. After the plastic sheet was removed, radon had apparently diffused from the pad resulting in a decrease of gamma-ray activity. The results were somewhat surprising since the uranium ore used in the pad was known to be a low emanator of radon. In addition, no radon emanation had been detected in samples of concrete collected during the construction of the pads. Subsequent measurements, however, strongly suggested that the variation in the uranium count rate on the uranium pad was largely the result of variations in atmospheric radioactivity which were found to occur in the early morning. Based on the initial interpretation of the results, it was decided that the pads should be sealed to prevent this apparent loss of radon. Sealing the pads also has the advantage of reducing seasonal moisture changes in the pads and the associated variation in their gamma-ray activity (Stromswald, 1978).

On 2 February 1985, all four pads were sealed with Jotun, Pioneer 200 chlorinated rubber paint. A rubber-based paint was selected because it would be flexible and less susceptible to cracking which would allow radon to escape. This particular paint had been used for several years on the exterior of concrete buildings in Bangkok with no signs of deterioration. The paint is also particularly good for restricting the movement of moisture and is used for sealing the concrete walls of swimming pools. Two coats of paint, thinned with approximately 20 per cent of the recommended chemical thinner were applied, the first in the morning and the second in the late afternoon. Each coat required approximately three gallons of paint for each pad. No radioactivity was found to be associated with the paint.

In order to investigate the effect of sealing the uranium pad on its gamma-ray activity, a series of measurements were carried out with a GR-410 portable spectrometer. These measurements were taken before the pads were

Table 18. Assigned pad concentrations

	K (pct)	eU (ppm)	eTh (ppm)
Blank	0.25 ± 0.01	0.91 ± 0.03	2.86 ± 0.05
K Pad	6.18 ± 0.06	1.46 ± 0.05	1.16 ± 0.06
U Pad	0.25 ± 0.01	16.21 ± 0.27	2.86 ± 0.05
T Pad	0.25 ± 0.01	2.54 ± 0.05	37.31 ± 0.42

The errors quoted take into consideration the number of samples analyzed. They also include a 1% uncertainty in the potassium and thorium laboratory calibration and a 1.5% uncertainty in the uranium (radium) calibration. It is also assumed that the analyses for the blank pad are the best estimates of the concrete matrix.

painted, after the first coat was applied and on several subsequent occasions. The results of the measurements on the blank pad are presented in Table 20, and show that the investigation of the effects of the sealing are complicated by diurnal fluctuations in airborne radioactivity. During the night, as the air is cooled and mixing of the air is reduced, the bismuth-214 which is attached to dust particles (and produces the gamma-ray activity) sinks closer to the ground thereby increasing the atmospheric gamma-ray activity at ground level. As the sun comes up in the early morning, the air is heated, thereby increasing the height of the mixing layer and reducing the radioactivity of the air.

Table 21 shows the calculated values of the uranium sensitivity of the GR-410 portable spectrometer before and after the pads were sealed. Errors in the uranium sensitivity arising from counting statistics are indicated. The ranges in the values (shown in brackets) arise from background variations which were determined by monitoring the blank pad. These atmospheric background variations are generally only significant in the early morning.

The results indicate that prior to the sealing of the pads there were fluctuations of 10 to 15 per cent in the gamma-ray activity of the uranium pad. For the first four months after the pads were sealed the gamma-ray activity of the uranium pad remained relatively constant. Sealing calibration pads was therefore considered a practical solution to the problem of the emanation of radon from uranium pads which has been found to cause problems at other calibration facilities (Løvborg, 1978; Stromswald, 1978). Sealing the pads gives the additional advantage that fluctuations in their moisture content are reduced, thereby minimizing changes in their gamma-ray activity. However, one year after painting, the gamma-ray activity of the uranium pad was again reduced indicating radon was being lost from the uranium pad. Periodic painting of the pads may therefore be necessary whenever any changes in gamma-ray activity of the uranium pad is observed.

Figure 21. Sealing the uranium pad with a plastic sheet.

Table 20. Variation of the uranium window count rate on the blank pad

Date	Time	U-Window (c/min.)
February 2/85	08:50 hrs.	60.9 ± 2.5
February 2/85	09:50 hrs.	50.6 ± 2.2
February 2/85	14:40 hrs.	42.0 ± 2.0
February 3/85	08:10 hrs.	58.4 ± 2.4
February 3/85	08:45 hrs.	53.4 ± 2.3
February 3/85	10:50 hrs.	40.2 ± 2.0
February 3/85	11:20 hrs.	42.3 ± 2.0

Dead-time considerations

The technique of multichannel analysis employed in gamma-ray spectrometers requires a finite time to process each pulse from the detectors. While one pulse is being processed, any other pulse that arrives will be rejected. Consequently, the actual 'live' time of a spectrometer is reduced by the time taken to process all the pulses reaching the analyzer. With modern electronics, the processing time for each pulse would be typically around 6 microseconds, but can be as high as 20 microseconds for older equipment.

For portable gamma-ray spectrometers measuring average levels of radioactivity, the count rates are so small that dead-time corrections can almost always be neglected. This is also true for measurements on the calibration pads whose gamma-ray activities are comparable to those of normal rocks and soils. However, this may not be the case for airborne gamma-ray spectrometers with their large volumes and associated high count rates. The calibration constants derived from measurements on the pads may be in error if dead-time corrections are not applied. This was found to be the case for the spectrometers used in the Thailand survey which were required to have a dead-time of less than 15 microseconds per pulse.

For some equipment, dead-time is measured electronically and is recorded digitally together with the spectral data. If this is not done, the dead-time of the equipment must be measured experimentally. A standard laboratory method for measuring the dead-time of a gamma-ray counter is the two source technique. With this technique, the count rates from two similar sources are first measured separately and then with both sources together. The count rate with both sources is found to be less than the sum of the individual count rates because of instrument dead-time. This dead-time can then be calculated from the observed count rates provided that the background count rate when no sources are present is negligible (Chase and Rabonowitz, 1968). However, with a large volume airborne spectrometer system, the count rates from the ground alone normally give rise to a significant dead-time without the

Table 19. The apparent effect of covering the uranium pad with plastic sheet

Uranium Window Count Rate		
December 5 - 17:30 hrs.	December 6 - 07:30 hrs.	December 6 - 11:00 hrs.
Before covering with plastic	14 hours after covering	3 hours after plastic removed
278.6 ± 5.3 c/min.	289.4 ± 5.4 c/min.	265.9 ± 5.2 c/min.

Table 21. The apparent uranium sensitivity of the GR-410 Portable Spectrometer before and after the pads were sealed

Date	Time	Sensitivity (cpm /ppm)	Comments
December 5/84	16:50 hrs.	15.6 ± 0.4	Before painting
February 2/85	09:00 hrs.	(12.7 - 13.4) ± 0.4	Before painting
February 2/85	14:50 hrs.	14.4 ± 0.4	After 1 coat
February 3/85	08:30 hrs.	(15.6 - 15.9) ± 0.4	After painting
February 3/85	11:00 hrs.	(15.0 - 15.2) ± 0.4	After painting
February 12/85	14:00 hrs.	15.5 ± 0.4	10 days after painting
June 16/85	-	16.1 ± 0.4	4 months after painting
January 20/86	-	13.1 ± 0.4	1 year after painting

addition of sources. An experimental technique has now been developed which allows the dead-time of a large airborne spectrometer to be calculated from total count window measurements, without the need for separate sources. This method was first suggested by Q. Bristow, who designed the GSC gamma-ray spectrometer system (Bristow, 1979), and has been successfully applied to the airborne spectrometers used in the Thailand survey. This method is in principal similar to the two-source technique, but in this case the background radioactivity acts as the two sources.

All three Thailand spectrometer systems have at least two detector boxes containing four 10.2 x 10.2 x 40.6 cm (4 x 4 x16 in.) prismatic detectors. The procedure to calculate the system dead-time is to first record the count rates in the total count window from two of these boxes of detectors separately over ground which is known to be uniformly radioactive. The count rates from the two boxes would normally be the same because their volumes are identical. The count rate is then measured again with both boxes operating. Because of the system dead-time the count rate from the combined detector systems is found to be less than the sum of the individual count rates. From these observed count rates, the dead-time of the system can be easily calculated.

For most multichannel analyzers currently used in airborne spectrometers, the time to process an individual detector pulse depends on its energy. In using the total count window to calculate the system dead-time, it is assumed that the dead-time of the system is proportional to the number of pulses registered in the total count window in one second. This is expected to be a good approximation for potassium, uranium and thorium gamma-ray sources, since the average energy deposited in the detector by these sources are similar (Fig. 2, 3 and 4). However, for a low energy source producing pulses which can be processed in a much shorter time, the dead-time may be quite different and not applicable to correcting the window count rates from potassium, uranium and thorium.

Let N_T be the total count rate recorded with both detector boxes operating and τ be the average time to process these pulses. The system takes a time, $N_T x \tau$, to process these N_T pulses and for this length of time cannot process any other pulses. Consequently the true count rate T_T is given by

$$T_T = \frac{N_T}{1-N_T\tau} \tag{26}$$

The true count rates T_1 and T_2 for the first and second box are given by similar formulae. However we know that

$$T_1 + T_2 = T_T \tag{27}$$

and consequently

$$\frac{N_1}{1-N_{1\tau}} + \frac{N_2}{1-N_{2\tau}} = \frac{N_T}{1-N_{T\tau}} \tag{28}$$

where N_1 and N_2 are the measured count rates for the first and second box. Equation (28) is a quadratic which can be readily solved to determine the dead-time per pulse, τ. It reduces to a particular simple form when N_1 and N_2 have the same value, N. In this case

$$\tau = \frac{2N - N_T}{N \times N_T} \tag{29}$$

The best estimate of N is given by the observed average count rate of both detector packages.

In calculating the dead-time per pulse it is important that the counts be accumulated for a sufficiently long time that the statistical error in the calculated value is reduced to an acceptable level. Almost all this error originates in the numerator of equation (29) due to the subtraction of two large numbers, both of which have errors due to counting statistics.

For a one second measurement, the error E in the calculation of τ can be shown to be given by

$$E = \frac{(2N + N_T)^{\frac{1}{2}}}{N \times N_T} \tag{30}$$

It is assumed that the errors in the calculation of $N \times N_T$ in equation 29 can be neglected.

Table 22. The effect of dead-time corrections on the calibration of an airborne spectrometer on the Thailand pads

Calibration Constant	No Dead-Time Correction	With Dead-Time Correction
Alpha	0.372	0.382
Beta	0.434	0.462
Gamma	0.918	0.944
a	0.078	0.093
b	0.008	0.012
g	0.055	0.059
K sens. (c/s/% K)	260.79	291.0
U sens. (c/s/ppm eU)	20.01	22.22
T sens. (c/s/ppm eTh)	14.78	16.79

If the value of τ is calculated using the total count rates from the average of n one second measurements, the percentage error in the dead-time, P, of each pulse is then given by

$$P = \frac{(2N + N_T)^{\frac{1}{2}}}{2N - N_T} \times \frac{100}{\sqrt{n}} \qquad (31)$$

It has been found that over ground of normal radioactivity by counting each detector package for 300 seconds, the dead-time of the spectrometers used in Thailand can be calculated to an accuracy of between 2 and 3 per cent. The effect of these dead-time corrections on the calibration of one of the airborne spectrometers is shown in Table 22.

Pulse pile-up considerations

The purpose of the calibration pads is to derive the shape of the gamma-ray spectrum of the three radioelements. However, the shape of these spectra may be distorted for an airborne spectrometer at ground level because of the high count rate. This distortion arises because of coincident pulses from the large volume detector array which arrives at the analyser and appears as one pulse. Two coincident low energy pulses are therefore analyzed as one higher energy pulse. Consequently, the observed spectrum appears to have a greater proportion of high energy gamma-rays than really exists. The amount of distortion due to these pulse pile-up effects increases with count rate and will be greater at ground level where the count rates are higher than at survey altitude.

The effect of count rates on the various calibration constants of the fixed-wing Islander spectrometer system was investigated. This system had two boxes containing four standard square cross-section detectors, and two boxes containing two detectors. After each measurement on the four calibration pads using all the detectors, a measurement was also carried out with only one detector box containing four detectors. The calculated calibration constants for the two different detector volumes are presented in Table 23. Dead-time corrections based on the total rate were applied to all the window count rates before the calculations were carried out.

The results show that the calibration constants are all lower with the smaller detector volume. This is because the spectral distortion is not so significant when the count rate is lower. At survey altitudes, the gamma-ray count rate is much lower than at ground level. Therefore the calibration constants for the smaller detector volume would be the best estimates of their true value at survey altitude. It is also important to realize that a spectrometer is calibrated by flying over ground of known concentration. When the spectrometer is flown over ground with similar proportions of the three radioelements, the correct ground concentrations will be found, even if the calibration constants are substantially in error. It is only in areas where the proportions of the radioelements are significantly different from the test strip that errors will develop.

Table 23. The effect of pulse pile-up on the calibration of an airborne spectrometer on the Thailand pads

Calibration Constant	Low Count Rate (4 Prismatic Detectors)	High Count Rate (12 Prismatic Detectors)
Alpha	0.367	0.387
Beta	0.436	0.474
Gamma	0.931	0.977
a	0.055	0.101
b	0.005	0.013
g	0.030	0.064

The value of b, which gives the ratio of the counts in the thorium window to those in the potassium window from a pure source of potassium should be zero, since potassium emits gamma-rays at only one energy. However, the large percentage differences in the value of b for the two detector assemblies has little effect on the count rate in the thorium window because the values are so small. Accordingly the differences between the calibration constants for the two different detector volumes must be considered in terms of the effect they have on the final analysis of the airborne system.

Recommended calibration procedure

In order to compare the results from the three airborne spectrometer systems, a standardized calibration procedure must be followed. Following discussions between Kenting Earth Sciences Ltd., the Project Implementation Office of DMR in Thailand and the GSC, a set of calibration procedures were prepared which satisfied both the technical requirements and the legal aspects of the contract. Two basic steps in these procedures relate to the use of the calibration pads. They are: 1) the determination of the stripping ratios of the airborne systems and 2) the calibration of the portable spectrometer used to monitor the airborne test range.

The procedure for calibrating an airborne system on the calibration pads is documented in Appendix A. These procedures include checking and tuning the system so that it is performing optimally and meets the requirements of the contract. Such things as the system resolution and any spectral drift of the system during the calibration need to be monitored. Tests were designed specifically for the Kenting spectrometers and may be significantly different for other systems and other survey requirements. They have been included to serve as a guide for monitoring similar airborne survey operations elsewhere.

The two helicopter systems consist of three similar detector packages. Two of these packages are mounted outside the helicopter, one on either side, with the third package mounted in the tail (Fig. 22). When the systems are calibrated, all three packages are close to the edges of the pad. In moving a detector from the centre of the pad to the

Figure 22. A helicopter showing a detector box near the edge of the pad.

edge, the radiation detected from the pad varies considerably. It is therefore important that the helicopter systems are placed in the same position on all four pads. This will ensure that the background radiation from the ground surrounding the pads will be the same on each pad which is an essential assumption in the calibration. It should be emphasized that the pads are only used to derive the shapes of the potassium, uranium and thorium spectra, the system sensitivities being derived from measurements over the airborne test range.

In order to ensure that the helicopter systems were placed in exactly the same place on all four pads, a line was painted on each pad to locate the helicopter skid (Fig. 23). The line was marked so that the two exterior side detector packages were at the same distance from the edge of the pad. The location of the skid along this line was marked so that the thorium window count rate over the thorium pad was a maximum. A location marker for the nose wheel of the fixed-wing system was also painted on each pad so that the detector packages inside the aircraft were located at the centre of each pad.

A measurement time of five minutes on each pad was selected to give at least 10 000 counts in all energy windows on all four pads thus errors in the window count rates due to random counting statistics should be less than one per cent.

As shown previously, the measurement of system dead-time is important in calibrating a large volume airborne spectrometer. This system dead-time depends on the number of pulses per second being processed by the multichannel analyzer. Most spectrometers have a lower level discriminator which restricts unwanted low energy pulses from being analyzed. Any variation in the position of this low energy discriminator will vary the number of pulses analyzed and will therefore affect the system dead-time. Part of the routine daily monitoring procedures was to position the lower level discriminator at an energy of 300 keV, which is just below the total count window (Table 1). This will eliminate unwanted pulses from the analyzer and at the same time minimize the system dead-time and maintain it at a constant value.

The procedure for measuring the system dead-time is described in Appendix B and may not be necessary for a system which records dead-time. The calibration with individual boxes of detectors to check on possible pulse pile-up effects were not included on a routine basis because of the considerable additional time required to perform the measurements.

Figure 23. Painting a line on the pads to locate the helicopter skid.

Appendix C shows the design of the form used to report the measurements for calculating the system dead-time. Some typical results are included to show how this calculation was performed. The form used to report the calibration results (Appendix D) shows a numerical example to illustrate how the measurements on all four pads are corrected for dead-time. The various calibration constants are calculated on the form shown in Appendix E. A program for a Hewlett-Packard 15-C calculator was found to be useful for calculating the calibration constant using a simple matrix method and is illustrated in Appendix F for the results reported in Appendix E.

The calibration of the portable spectrometer used to monitor the airborne test range is relatively straight forward compared to an airborne system because of its small detector volume and simpler design. The routine procedure consisted of carrying out ten minutes of measurements on each pad, commencing with the blank pad. The blank pad was repeated at the end of the series of measurements to check that the atmospheric background had remained the same. Instead of carrying out one ten-minute measurement on each pad, five individual measurements of two minutes were performed. Analysis of the individual readings allows any equipment malfunction to be readily detected.

The detector was kept from direct contact with the ground by a piece of 10-cm-thick lightweight rigid foam so that a large volume of the ground is sampled. The five measurements on each pad were all made near the centre but the detector was moved for each measurement to average out any possible inhomogeneities in the surface radioactivity of the pad. The calibration constants for the portable spectrometer were calculated using the method illustrated in Appendix E.

DISCUSSION

Comparative study

How good are the calibration pads in Thailand and how do they compare with facilities elsewhere? To answer these questions the uncertainties in the calibration constants determined using the Thailand pads need to be compared with those from other facilities. These uncertainties were calculated theoretically by simulating a series of calibration measurements using a portable gamma-ray spectrometer. The particular gamma-ray spectrometer chosen was a GR-410 which had been used in an international comparison of calibration facilities throughout the world by L. Løvborg of the Risø National Laboratory, Denmark working under a research contract for the International Atomic Energy Agency (Løvborg, 1984). Using the calibration constants obtained from this worldwide intercomparison, which are shown in Table 24, the count rates of this particular spectrometer could be derived on any calibration pads of known concentration. From these simulated measurements the calibration constants and their respective errors were calculated by means of a computer program PADWIN developed at the Risø National Laboratory (Løvborg, 1982).

Errors in the calculated calibration constants are due both to counting statistics and uncertainties in the pad concentrations. In this particular study the counting time of the spectrometer was set to 10 000 seconds to effectively eliminate errors due to counting statistics. The calibration errors from the simulated measurements at the different facilities are then solely governed by uncertainties in the pad concentrations and do not depend on the counting time.

Table 24 shows the percentage errors that would arise when calibrating a portable gamma-ray spectrometer on three airborne spectrometer calibration facilities in Thailand, Canada (Grasty and Darnley, 1971) and the USA (Ward, 1978). The results clearly show that all the calibration constants can

Table 24. Errors associated with the calibration of a GR-410 portable spectrometer at various calibration facilities

Calibration Constant	Input Value	Percentage Error Thailand	United States	Canada
Alpha	0.586	3.5	1.7	5.9
Beta	0.484	3.9	3.8	41.7
Gamma	0.769	1.5	1.8	33.6
a	0.0351	3.3	7.4	7.4
K Sens. (c/s/pct)	3.36	1.1	1.4	39.7
U Sens. (c/s/ppm)	0.325	2.7	2.4	10.3
T Sens. (c/s/ppm)	0.128	1.3	1.0	8.6

The errors indicated do not include counting statistics and only result from uncertainties in the pad concentrations.

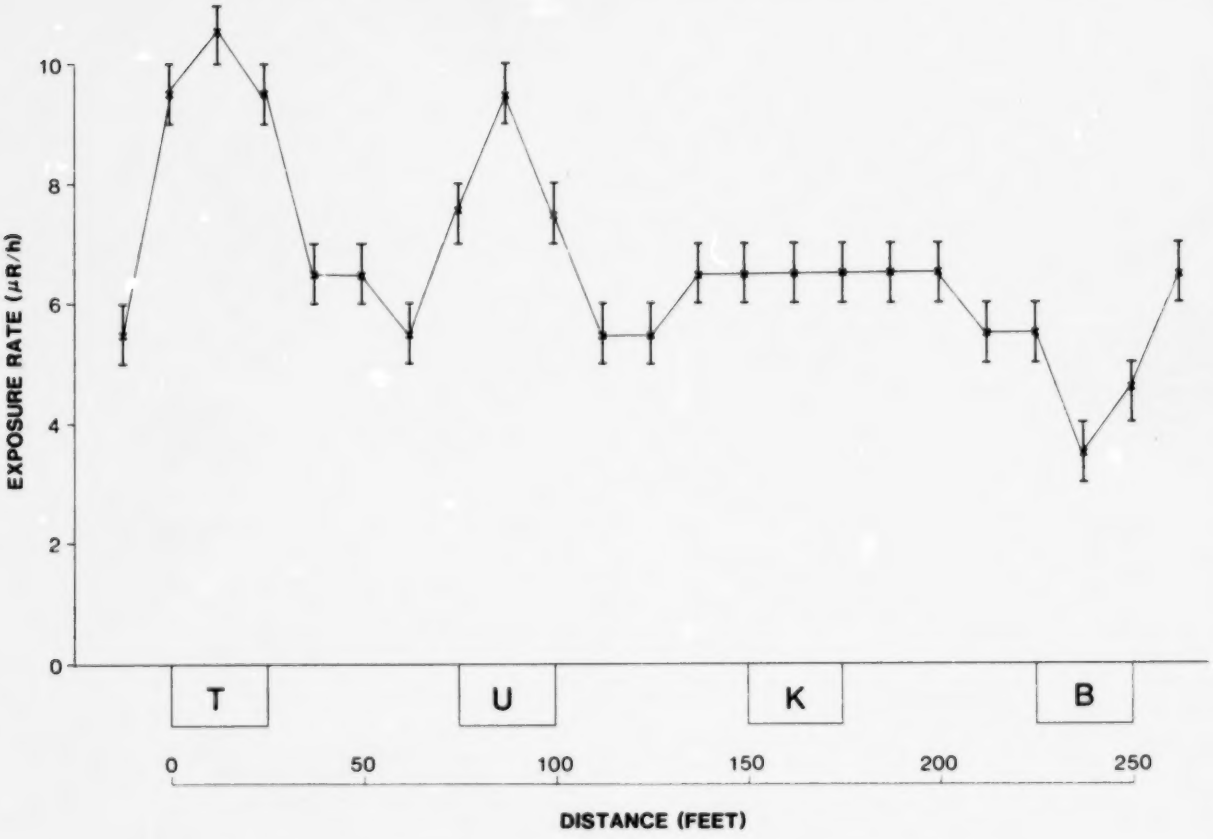

Figure 24. Profile of the exposure rate measured over the calibration pads.

be derived more reliably on the Thailand pads than on the Canadian pads. The large errors in the stripping ratios, beta and gamma on the Canadian pads arise because there is no potassium pad. Consequently the potassium sensitivity and the associated contribution of potassium to the uranium and thorium window on all five pads cannot be reliably determined. The comparison between the four Thailand and five United States pads show them to be comparable even though only four pads are used in Thailand. This is because the Thailand pads are relatively pure in their respective radioelements and therefore errors in the calibration are minimized.

Environmental considerations

The radiation levels to which people are subjected when using the calibration facility is naturally of concern to those unfamiliar with the health aspects of radioactivity. This concern arises because the pads are used as a gamma-radiation standard and were manufactured with ore grade uranium and thorium which in its undiluted state is considered radioactive and must be transported with strict controls.

In order to assess the radiation levels on the pads, a series of measurements were taken on 30 October 1984, approximately four months after the pads were constructed.

Table 25. Measured and calculated exposure rate on the Thailand pads

PAD	Concentrations K(%)	U(ppm)	Th(ppm)	Exposure Rate (μR/hr) - Blank Pad Measured[1]	Calculated[2]
K-B	5.93	0.55	-1.7	3.3 ± 0.5	7.7
U-B	0	15.3	0	6.6 ± 0.5	8.5
T-B	0	1.63	34.45	7.7 ± 0.5	9.4

[1] The results shown are for a calibration with a radium source and may be in error particularly for potassium because of the response of the scintillometer to radiation of different energies (IAEA, 1976).

[2] The values were calculated using the relationship (Lovborg, 1984):

1% K = 1.31 μR/hr
1 ppm U = 0.552 μR/hr
1 ppm Th = 0.246 μR/hr

These measurements were performed by Mr. S. Bunnak and Mr. S. Komolsuk from the office of the Atomic Energy for Peace using a standard scintillometer manufactured by General Radiological Ltd. of London. The measurements, shown in Figure 24 were taken at ground level at 25-foot intervals on a line through the centre of the four pads. They included measurements at the centre of each pad to achieve the maximum radiation levels that could be encountered, as well as measurements at the edges of each pad and on the adjacent ground where the effect of the pads were negligible.

The instrument was calibrated with a cesium source of known activity. Later calibration with a radium source showed a difference in the calibration of ten per cent. However, even with a radium source, the calibration may not be reliable, particularly for radiation from potassium because of the response of the instrument to gamma-radiation of different energy (IAEA, 1976). For this reason the exposure rate was also calculated at the centre of the potassium, uranium and thorium pad from their measured concentrations. This was achieved using data presented by Løvborg (1984) for a circular pad of diameter 8 m which corresponds closely to the area of the Thailand pads. The results of these calculations and the measured values are shown in Table 25. They are presented using the blank pad as a zero reference, by subtracting both the concentrations and the exposure rate of the blank pad from the measurements (calculated and experimental) on the other three pads. With this procedure, the unknown effect of the ground surrounding the calibration pads can be effectively eliminated.

The results, both measured and calculated show that the thorium pad will produce the highest radiation levels. The large discrepancy between the measured and calculated exposure rate on the potassium pad illustrates the problem of measuring exposure rate with a scintillometer calibrated with a source with a different gamma-radiation energy distribution.

In order to assess the radiation dose received by a person on the pads, it is necessary to convert exposure rate to radiation dose for which the units are millirems. A person will receive a whole body dose of approximately one millirem when exposed to gamma-radiation of one milli-Roentgen. In the United States, the maximum allowable whole body dose is 100 millirem in any seven consecutive days (Ward, 1978). The maximum levels are similar in other countries. A person who remains at the centre of the thorium pad for seven consecutive days where the exposure rate is approximately 10 μR/hr will receive a total radiation dose of 1.7 millirems. This is far below the maximum allowable dose of 100 millirems. There are therefore no radiation health risks for persons using these calibration facilities.

Radon loss from the uranium pad

The loss of radon from the uranium pad was somewhat surprising, particularly because great care had been taken in the selection and preparation of the uranium ore to avoid such a problem.

A survey of calibration facilities throughout the world (Løvborg, 1984) indicated a uranium ore should be selected which emanated less than about 2 per cent of its radon. The loss of radon from the uranium pad in Denmark (Løvborg, 1978) was believed to be due to the high percentage of fine particles of ore which were less than 40 μm which allow radon to escape through the recoil effect in the alpha decay. The uranium ore used in the Thailand pads was known to be a low emanator of radon (Grasty and Dyck, 1984) and the fine particles less than 74 μm had been removed to avoid problems due to grain size.

In an attempt to understand why radon loss had occurred, approximately half a dozen small pieces of concrete were chipped off the edge of the uranium pad and brought back to Ottawa for analysis. The analysis was carried out by Dr. P. Mainwaring using the scanning electron microprobe facility at the Canada Centre for Mineral and Energy Technology (CANMET).

It proved difficult to locate any uranium grains. Far fewer grains were found than would be expected on the basis of the quantity of uranium ore in the concrete. Eventually two grains were found, one of which appeared to be relatively fresh and angular (Fig. 25) and the other partially decomposed (Fig. 26). The photographs are backscattered electron images wherein minerals with a high average atomic number appear bright. The grain in Figure 25 is approximately 130 μm long and the partially decomposed grain in Figure 26 is approximately 80 μm long. The bright areas at the edge of some of the small grains in Figure 26 are an edge effect.

Analysis of the concrete near the relatively fresh grain (Fig. 25) showed that uranium was present at least as far as 5 μm from the grain boundary. This result, together with the

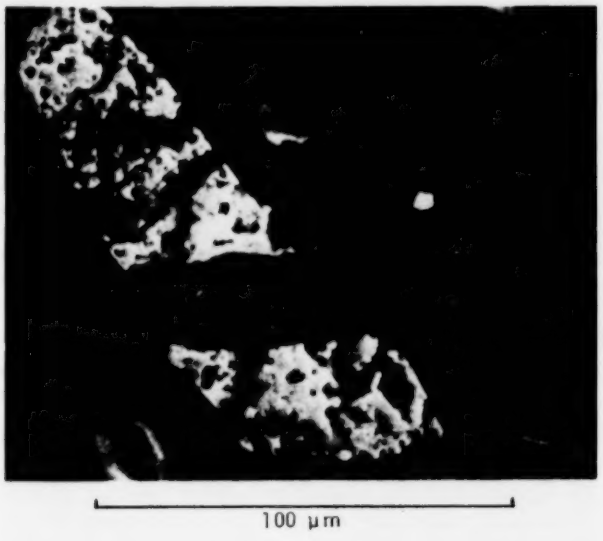

Figure 25. An electron backscattered image of a relatively fresh uraninite grain.

Figure 26. An electron backscattered image of a partially decomposed uraninite grain.

lack of uranium grains and the obvious decomposition of grains, which were initially fresh and angular, demonstrates that the uranium grains are apparently being decomposed by the alkaline gels in the concrete. This chemical attack of the uranium grains was observed through fluctuations in the gamma-ray activity of the uranium pad in the short space of four months from the date of construction of the pads. In the tropical climate of Thailand where the temperature and humidity is high throughout the year, this chemical process would be expected to proceed at a much faster rate than in a more temperate climate.

A partial loss of radon from the uranium pad will have a negligible effect on the calibration of an airborne gamma-ray spectrometer system because the pads are used to derive the stripping ratios of the system and not the sensitivities. This is because the Thailand pads are relatively pure in their respective radio-elements and the stripping ratios are derived from the shapes of the potassium, uranium and thorium spectra. Of course, the sensitivities of the portable spectrometer are required to monitor the test strip used to derive the aircraft system sensitivities at the survey altitude. Clearly, there is a need to investigate the problem arising from the decomposition of uranium grains by the alkaline gels in the concrete, particularly for tropical environments.

RECOMMENDATIONS FOR PAD CONSTRUCTION

In the successful construction of the Thailand calibration facilities, various aspects were felt to have played a significant role. As would be expected for a project of this magnitude, there were also some aspects where improvements could be made. The following recommendations are made for the construction of similar facilities elsewhere. More specific details on these recommendations may be found in the text.

1. Site Selection:

   A detailed survey of the site should be carried out with a total count scintillometer to establish that the area is uniform in radioactivity.

2. Dimensions: Four pads 8 x 8 x 0.5 m and 15 m apart.

3. Ideal Concentrations:

   Blank pad - Low Radioactivity
   Potassium pad - 8 per cent potassium
   Uranium pad - 20 ppm uranium
   Thorium pad - 40 ppm thorium.

4. Construction Materials:

   Blank pad - Low radioactivity sand and cement
   Potassium pad - Potassium feldspar and cement
   Uranium pad - Low radioactivity sand, cement and uranium ore
   Thorium pad - Low radioactivity sand, cement and thorium ore.

   To be mixed in the ratio of three parts sand (or feldspar) to one part cement.

5. Uranium Ore:

   A high concentration uranium ore which emanates less than about 2 per cent of its radon and has a low thorium content.

6. Thorium Ore:

   A high concentration thorium ore with a low uranium content e.g., monazite beach sand or thorite.

7. Grain Size:

   Sand - A typical masonry sand with a range of particles from 0.25 to 2 mm.

   Uranium Ore - The ore should be crushed so that approximately 10 000 grains are in each concrete sample taken for analysis. The fine fraction less than 0.074 mm (200 mesh), should be discarded to avoid any possible radon loss.

   Thorium Ore - To be prepared in the same way as the uranium ore. A monazite beach sand will have a suitable grain size distribution.

   Potassium - The potassium feldspar should be crushed to give a similar grain size distribution as the masonry sand. The fine fraction, less than 0.074 mm (200 mesh), should be discarded.

8. Blending:

   A two stage blending procedure of the dry materials is recommended for the uranium and thorium ores.

   First dilute the uranium ore to 500 ppm and the thorium ore to 1000 ppm with low activity sand of similar grain size.

   For efficient blending the mixer should be less than half full and the ore and sand added in small quantities in the correct proportions.

   Check the homogeneity of the uranium and thorium concentrates before they are used in the construction.

9. Construction Procedures:

   The pads should be constructed in the following order, 1) blank pad, 2) potassium pad, 3) uranium pad, 4) thorium pad.

   For efficient blending, the dry materials should be added to the cement trucks, in the correct proportions, a little at a time.

   Sufficient water should be added to the trucks for a low slump sand-cement mix which is sufficiently workable to spread across the area of the pads.

10. Pad Analyses:

Approximately 36 samples should be taken from the blank and potassium pad and 72 samples from the uranium and thorium pad.

The samples should be left to dry naturally before being sealed for gamma-ray analysis.

11. Radon Loss:

The pads should be sealed with a flexible waterproof paint to reduce radon loss and fluctuations in their moisture content. It may be necessary to repaint the pads periodically whenever any changes in gamma-ray activity of the uranium pad is observed.

ACKNOWLEDGMENTS

I am particularly grateful to the Department of Mineral Resources, Thailand and Kenting Earth Sciences Ltd. for permission to publish this report which will hopefully serve as a useful practical document for those wishing to construct similar facilities elsewhere.

This project could not have been carried out without the valuable advice and co-operation of many people. To all these people I would like to express my appreciation for their help.

All the communications between the GSC and the construction contractor in Thailand were carried out through J. Irvine of Kenting Earth Sciences Ltd. who also provided useful practical suggestions on the proposed construction procedures.

J. Wilson of Kenting and P.G. Killeen of the GSC spent considerable time preparing and documenting the monitoring and calibration procedures for the entire airborne operation. In addition, P.G. Killeen provided moral and practical support during the construction operation and J. Wilson provided the stimulus for carrying out the experiment of sealing the uranium pad with plastic sheet.

During the construction procedures many people from DMR provided valuable practical assistance in carrying out such tasks as weighing and checking bags of material, taking samples, performing gamma-ray spectrometer measurements, and a multitude of other chores. I would particularly like to thank Satien Sukontapongpow for his willing co-operation, valuable advice, and the hard work he performed during the hectic two days of construction. Similar thanks are owed to the large number of DMR personnel without whose help the project would not have come to such a satisfactory conclusion.

B.W. Charbonneau of the GSC organized all the grain size analyses and mineral identification of the construction materials which were carried out at the GSC. Q. Bristow also of the GSC first suggested the method of measuring the dead-time of the airborne gamma-ray spectrometers and provided constructive criticisms of this particular section in the report.

I would particularly like to thank Dr. P. Mainwaring at CANMET who spent a considerable amount of his valuable time carrying out the scanning electron microprobe studies of the concrete samples. Last, but not least, I would like to thank my two daughters, Michelle and Shelley, who assisted me over two week-ends in analyzing the U-500 and T-1000 ore concentrates.

REFERENCES

Bristow, Q.
1979: A gamma ray spectrometry system for airborne geological research; in Current Research, Part C, Geological Survey of Canada, Paper 79-1C, p. 55-61.

Burson, Z.G.
1973: Airborne surveys of terrestrial gamma radiation in environmental research; IEEE Transactions on Nuclear Science, v. NS-21(1).

Chase, G.D. and Rabinowitz, J.L.
1968: Principles of radioisotope methodology; Burgess Publishing Company, Minneapolis, 633 p.

Darnley, A.G., Bristow, Q., and Donhoffer, D.K.
1968: Airborne gamma-ray spectrometer experiments over the Canadian Shield; in Nuclear Techniques and Mineral Resources (International Atomic Energy Agency, Vienna), p. 163-186.

Faye, G.H., Bowman, W.S., and Sutarno, R.
1979: Uranium ore BL-5 – A certified reference material; CANMET Report 79-4, CANMET, Energy, Mines and Resources Canada, 11 p.

Grasty, R.L. and Darnley, A.G.
1971: The calibration of gamma-ray spectrometers for ground and airborne use; Geological Survey of Canada, Paper 71-17, 27 p.

Grasty, R.L. and Dyck, W.
1984: Radioactive equilibrium studies on four Canadian uranium reference ores; in Current Research, Part A, Geological Survey of Canada, Paper 84-1A, p. 53-56.

Grasty, R.L., Bristow, Q., Cameron, G.W., Dyck, W., Grant, J.A., and Killeen, P.G.
1982: Primary calibration of a laboratory gamma-ray spectrometer for the measurement of potassium, uranium and thorium; Proceedings of OECD and IAEA Symposium on Uranium Exploration Methods, Paris, p. 699-712.

IAEA
1976: Radiometric reporting methods and calibration in uranium exploration. Technical Report Series no. 174 (International Atomic Energy Agency, Vienna), 57 p.

Killeen, P.G.
1979: Gamma-ray spectrometric methods in uranium exploration – application and interpretation; in Geophysics and Geochemistry in the Search for Metallic Ores (P.J. Hood, ed.); Geological Survey of Canada, Economic Geology Report 31, p. 163-229.

King, L.V.
1912: Absorption problems in radioactivity; Philosophical Magazine, v. 23, p. 242.

Kogan, R.M., Nazarov, I.M., and Fridman, Sh.D.
1971: Gamma spectrometry of natural environments and formations – theory of the method, applications to geology and geophysics; Israel Program for Scientific Translations, 5778, Jerusalem.

Løvborg, L., Bøtter-Jensen, L., and Kirkegaard, P.
1978: Experiences with concrete calibration sources for radiometric field instruments; Geophysics, v. 43, p. 543-549.

Løvborg, L.
1982: Error analysis of calibration and field trials with spectrometers and counters; Uranium Exploration Methods (OECD, Paris), p. 671-680.

1984: The calibration of portable and airborne gamma-ray spectrometers – theory, problems, and facilities; Risø Report 2456, 207 p.

Multala, J.
1981: The construction of gamma-ray spectrometer calibration pads; Geoexploration, v. 19, p. 33-46.

Pitkin, J.A.
1968: Airborne measurements of terrestrial radioactivity as an aid to geological mapping; U.S. Geological Survey, Professional Paper 516-F.

Stromswold, D.C.
1978: Monitoring of the airport calibration pads at Walker Field, Grand Junction, Colorado for long-term radiation variations; GJBX-99(78), Bendix Field Engineering Corp., 35 p.

Tanner, A.B.
1980: Radon migration in the ground: A supplementary review. Natural Radiation Environment III (Technical Information Center, U.S. Department of Energy), v. 1, p. 5-56.

Ward, D.L.
1978: Construction of calibration facility Walker Field, Grand Junction, Colorado; ERDA Open File GJBX-37(78).

APPENDIX A

Calibration Pads – Procedure

N.B.: Whenever calibration sources are being used, at least one source should be placed near each detector package.

1. Arrange with the Project Implementation Office for an inspector to be present.
2. Position aircraft at markers on background pad.
3. Check that all detectors have cesium resolution $\leq$12%.
4. Adjust gain of each detector so that the cesium peak falls in channel 55.
5. With all detectors on, check that the cesium resolution is <12% with the background removed.
6. With thorium sources, set the Lower Level Discriminator (LLD) at 300 Kev (ch 25 +/- 4). LLD is the lowest channel to contain in excess of 50 cps.
7. Set Upper Level Discriminator (ULD) at $\geq$2880 Kev ($\geq$ ch 240). ULD is the highest channel to receive some counts.
8. Adjust system gain so that thorium peak is in channel 218 +/- 2.
9. With cesium sources, adjust the fine zero so that the cesium peak falls in channel 55 +/- 1.
10. Repeat steps 8 and 9 until no further adjustment is required.
11. Record channel numbers of cesium and thorium peaks and system resolution on cesium.
12. With sources more than 20 m away, record at least five minutes of one second data on magnetic tape.
13. Check that the thorium peak has not drifted by more than two channels from that recorded in step 11.
14. Move to marks indicated on the potassium pad.
15. Check that the system resolution at cesium is $\leq$12% with background removed and repeat steps 8 to 13.
16. Repeat steps 14 and 15 for the uranium and thorium pads.

APPENDIX B

Dead-time Determination – Procedure

The following procedure will be performed twice. Once on the background pad using cesium sources and again on the thorium pad with no sources. The cesium dead-time will show the performance of the instrument and the thorium dead-time will more closely approximate that existing under survey conditions and will be used in data compilation.

a) For helicopters, record on magnetic tape one second data for two minutes with:

1. only the left box on.
2. only the right box on.
3. both the left and right boxes on.

b) For the Islander, record on magnetic tape one second data for two minutes with:

1. only the forward box of four crystals on.
2. only the aft box of four crystals on.
3. both the forward and aft boxes of four crystals on.

The expression for dead-time is:

$$\tau = \frac{2C_a - C_t}{C_a C_t}$$

where
C_a = average of count rate from each box.
C_t = count rate with both boxes together.

APPENDIX C

Dead time determination – Results

AIRCRAFT: _____ DATE: _____ TIME: _____

OPERATOR: _____ TEMPERATURE: _____

WEATHER COMMENTS: _____

CESIUM

	Box 1 (C_1)		Box 2 (C_2)		Combined (C_t)	
	Time	T.C.	Time	T.C.	Time	T.C.
Accumulated						
Av. cps.		1657.7		1719.4		3311.4

$$C_a = \frac{C_1 + C_2}{2} = \frac{1657.7 + 1719.4}{2} = 1688.6 \text{ cps}$$

Calculated Dead Time Cs $\tau = \frac{2C_a - C_t}{C_a C_t} = \frac{2 \times 1688.6 - 3311.4}{1688.6 \times 3311.4} = 11.8$ μ secs/pulse

THORIUM

	Box 1 (C_1)		Box 2 (C_2)		Combined (C_t)	
	Time	T.C.	Time	T.C.	Time	T.C.
Accumulated						
Av. Cps.		3255.4		3195.4		6211.9

$$C_a = \frac{C_1 + C_2}{2} = \frac{3255.4 + 3195.4}{2} = 3225.4 \text{ cps}$$

Calculated Dead Time Th $= \frac{2C_a - C_t}{C_a C_t} = \frac{2 \times 3255.4 - 6211.9}{3255.4 \times 6211.9} = 14.8$ μ secs/pulse

APPENDIX D
Calibration Pads – Results

AIRCRAFT: _____ DATE: _____ TIME: _____

OPERATOR: _____ TEMPERATURE: _____

WEATHER COMMENTS: _____

RAW PAD MEASUREMENTS

Accumulated	Time	T.C.	K.	U.	Th
Blank Pad					
K Pad					
U Pad					
T Pad					

Average cps.	T.C.	K.	U.	Th	% Dead Time
Blank Pad	2331.91	215.55	87.00	85.64	2.77
K Pad	7964.27	1761.27	173.64	73.45	9.48
U Pad	7112.82	496.64	393.09	109.45	8.46
T Pad	9111.91	466.27	309.09	597.36	10.84

Dead Time Corrected Average cps.	K.	U.	Th
Blank Pad	221.70	89.48	88.08
K Pad	1945.67	191.82	81.14
U Pad	542.56	429.44	119.57
T Pad	522.98	346.68	670.01

APPENDIX E

Computation of Calibration Factors (Matrix Method)

Average cps.	K	U	T
K - Blank	1723.97	102.34	-6.94
U - Blank	320.86	339.91	31.49
T - Blank	301.28	257.20	581.93

$$\begin{bmatrix}\text{COUNTS}\\ \text{(blank pad removed)}\end{bmatrix} = \begin{bmatrix}\text{SENSITIVITY}\end{bmatrix} \times \begin{bmatrix}\text{CONCENTRATION}\\ \text{(blank pad removed)}\end{bmatrix}$$

$$\begin{array}{l} \\ \text{K pad} \\ \text{U pad} \\ \text{T pad} \end{array} \begin{array}{c} \begin{array}{ccc} \text{K cnts} & \text{U cnts} & \text{T cnts} \end{array} \\ \begin{bmatrix} 1724.0 & 102.3 & 06.94 \\ 320.9 & 339.9 & 31.5 \\ 301.3 & 257.2 & 581.9 \end{bmatrix} \end{array} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{array}{c} \begin{array}{ccc} \text{K conc} & \text{U conc} & \text{T conc}^1 \end{array} \\ \begin{bmatrix} 5.93 & 0.55 & -1.7 \\ 0 & 15.30 & 0 \\ 0 & 1.63 & 34.45 \end{bmatrix} \end{array}$$

where

$$\alpha = \frac{a_{32}}{a_{33}} = \frac{6.415}{16.79} = 0.382 \qquad a = \frac{a_{32}}{a_{22}} = \frac{2.059}{22.22} = 0.093$$

$$\beta = \frac{a_{31}}{a_{33}} = \frac{7.754}{16.79} = 0.462 \qquad b = \frac{a_{13}}{a_{11}} = \frac{3.453}{291.0} = 0.012$$

$$\gamma = \frac{a_{21}}{a_{22}} = \frac{20.97}{22.22} = 0.944 \qquad g = \frac{a_{12}}{a_{11}} = \frac{17.03}{291.0} = 0.059$$

and sensitivities[2] are given by

K sens = a_{11} = 291.0 cps/%k

U sens = a_{22} = 22.22 cps/ppm eU

T sens = a_{33} = 16.79 cps/ppm eTh

[1] These concentrations are for the U-Tapao pads.
[2] These are ground level sensitivities and are not the values to be used at the survey altitude.

APPENDIX F

Hewlett-Packard 15C Computer Program to Calibrate a Spectrometer on the Thailand Pads

PROBLEM: To solve matrix equation given in Appendix E.

$$\begin{bmatrix}\text{COUNT MATRIX}\\ A\end{bmatrix} = \begin{bmatrix}\text{SENSITIVITY}\\ \text{MATRIX } B\end{bmatrix} \times \begin{bmatrix}\text{CONCENTRATION}\\ \text{MATRIX } C\end{bmatrix}$$

Keystrokes	Display	Comments
3 ENTER f DIM A	3.00000	Dimension matrix A to be 3x3
f MATRIX 1	3.00000	Prepares for automatic entry of matrix f USERelements.
1724 STO A	A 1,1	Denotes matrix A, row 1, column 1
	1724.0	Stores a_{11}, K window counts, K-pad-Blank
102.3 STO A	102.3	Stores a_{12} U window counts, --
6.94 CHS STO A	-6.94	Stores a_{13}, T window, --
320.9 STO A	320.9	Stores a_{21}, K window, U-pad-Blank
339.9 STO A	339.9	Stores a_{22}, U window, --
31.5 STO A	31.5	Stores a_{23}, T window, --
301.3 STO A	301.3	Stores a_{31}, K window, T-pad-Blank
257.2 STO A	257.2	Stores a_{32}, U window, --
581.9 STO A	581.9	Stores a_{33}, T window, --
3 ENTER f DIM C	3.000	Dimension matrix C to be 3x3
5.93 STO C	C 1,1	Denotes matrix C, row 1, column 1
	5.93	Stores C_{11}, K conc, K-pad-Blank
0.55 STO C	0.55	Stores C_{12}, U conc, --
1.7 CHS STO C	-1.7	Stores C_{13}, T conc, --
0 STO C	0	Stores C_{21}, K conc, U-pad-Blank
15.3 STO C	15.3	Stores C_{22}, U conc, --
0 STO C	0	Stores C_{23}, T conc, --
0 STO C	0	Stores C_{31}, K conc, T-pad-Blank
1.63 STO C	1.63	Stores C_{32}, U conc, --
34.45 STO C	34.45	Stores C_{35}, T conc, --
f RESULT B	34.45	Designates matrix B for storing result
RCL MATRIX A	A 3 3	Enters description for A, 3x3 matrix
RCL MATRIX C	C 3 3	Enters description for C, 3x3 matrix into the X-register, B into Y-register
÷	running	Temporary display while $C^{-1}A$ is being calculated
	B 3 3	Description for the result matrix B, the 3x3 sensitivity matrix
RCL B	B 1,1	Denotes matrix B, row 1, column 1
	291.0	Value of B_{11}, K sensitivity
RCL B	17.03	Value of B_{12}, U window sensitivity to K
RCL B	3.453	Value of B_{13}, T window sensitivity to K
RCL B	20.97	Value of B_{21}, K window sensitivity to U
RCL B	22.22	Value of B_{22}, U sensitivity
RCL B	2.059	Value of B_{23}, T window sensitivity to U
RCL B	7.754	Value of B_{31}, K window sensitivity to T
RCL B	6.415	Value of B_{32}, U window sensitivity to T
RCL B	16.79	Value of B_{33}, T sensitivity

Energy, Mines and Resources Canada
Energie, Mines et Ressources Canada